National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology

Microdevices LABORATORY

25 YEARS OF **INNOVATION**

2014 ANNUAL REPORT

25 YEARS OF INNOVATION

We are proud that for the past 25 years, JPL's **MICRODEVICES LABORATORY** (MDL) has made seminal contributions in the areas of diffractive optics, detectors, nano and micro systems, lasers, and focal planes with breakthrough sensitivity from deep UV to submillimeter, as a result of the dedication and hard work of a great number of talented scientists, technologists, and research staff. Through this research and development, MDL has produced novel and unique components and subsystems enabling remarkable achievements in support of NASA's missions and other national priorities. We are excited to have been a part of this important work and look forward to many years of continued success.

MICRODEVICES.JPL.NASA.GOV

CELEBRATING MDL'S 25TH ANNIVERSARY

1991 | 2001 | 2006 | 2010 | 2015

1991
NASA's Upper Atmosphere Research Satellite (UARS) with JPL's Microwave Limb Sounder (MLS) with MDL-fabricated components. The first instrument to directly measure and provide global information on chlorine monoxide (ClO), the dominant form of chlorine that destroys ozone.

1995
Kuiper Airborne Observatory (KAO). MDL-fabricated heterodyne receivers obtained the first direct detection of the fundamental transition of molecular water in interstellar space.

1996
Nike-Orion Sounding Rocket. The HOMER (High-Altitude Ozone Measuring and Educational Rocket) instrument suite included an advanced delta-doped CCD from MDL that measured the concentration in Earth's upper atmosphere of ozone and other constituents affecting ozone.

1997–2003
Balloon Observations of Millimetric Extragalactic Radiation and Geophysics (BOOMERANG). MDL-fabricated micromesh spider-web bolometers on these missions made unprecedented measurements of the cosmic microwave background and showed for the first time that the universe is "flat."

2000
Earth Observing 1 (EO-1) Hyperion high-resolution hyperspectral imager. MDL e-beam grating enabled more accurate remote mineral exploration, better predictions of crop yield and assessments, and better data for environmental management.

2000
Space Technology Research Vehicle (STRV-1D). An MDL-fabricated quantum well infrared photodetector (QWIP) focal plane array was flown successfully, testing this new technology in the harsh environment of orbit.

2001
Genesis Mission. MDL coated and shape verified over 25% of the collector arrays, which absorbed and returned solar wind particles to understand and chemically model the evolutionary transformations of the solar nebula over the last 4.6 billion years.

2003–2008
Black Brant IX Sounding Rocket. A delta-doped CCD in the Long-Slit Imaging Dual Order Spectrograph (LIDOS) was flown on three separate sounding rocket missions. The UV-sensitive detector successfully recorded star spectra and scattered light from nebular material of the Orion Nebula (M42).

2004
Rosetta Orbiter. The Microwave Instrument for the Rosetta Orbiter (MIRO) incorporated a spectrometer with a 557-GHz radiometer with subharmonic planar diode mixers and multipliers fabricated in MDL and measured outgassing rates of gases from comet Churyumov-Gerasimenko.

2004
Aura: The Earth Observing System (EOS) Microwave Limb Sounder (MLS) with MDL-fabricated 190/240/640-GHz and 2.5-THz mixers enables measurements of molecular species providing improved understanding of stratospheric ozone chemistry and stability, predictions of climate change and variability, and mapping of global air quality.

2005
Mars Reconnaissance Orbiter (MRO). MDL-fabricated curved gratings and uncooled IR thermopile detectors on the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument and the Mars Climate Sounder (MCS) instrument, respectively, defined the mineralogy of Gale Crater, allowing selection of the Curiosity rover landing site, and provided the longest unbroken global temperature, dust, and water ice climatology for the atmosphere of Mars (> 8 years).

2007
Phoenix Mars Lander. MDL-developed technologies on the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) instrument provided soil sample analysis at the Mars polar ice cap and found evidence of mineral nutrients essential to life in the Martian soil.

2008
Chandrayaan-1. The Moon Mineralogy Mapper (M3) instrument used enabling MDL-fabricated curved gratings for the imaging spectrometer that provided the first high-resolution spatial and spectral map of the entire lunar surface, revealing its mineral composition and the first indication of surficial water in the lighted areas of the Moon.

2009
Herschel Space Observatory. MDL enabling detectors on the Spectral and Photometric Imaging Receiver (SPIRE) and Heterodyne Instrument for the Far-Infrared (HIFI) have been providing data of unprecedented precision since launch. HIFI detected water vapor on Ceres, in a torus around Enceladus, and around a nearby star; water from comet Hartley 2 of the same isotopic composition as that of Earth; and discovered many new molecules in interstellar space. SPIRE provided large-area sky maps detecting distant infrared-luminous galaxies and detected argonium—ArH+, the first interstellar molecule containing a noble gas element.

2009
LRO (Lunar Reconnaissance Orbiter). MDL-fabricated thermopile detectors on the Diviner Lunar Radiometer Experiment instrument identified cold traps (areas cold enough to preserve ice for billions of years), potential ice deposits, rough terrain, and rock abundance; mapped compositional variations on the surface; and derived subsurface temperatures.

2009
Planck. MDL-fabricated spider-web and polarization-sensitive bolometers on the High Frequency Instrument (HFI) allowed high-precision photometry and polarimetry of the cosmic microwave background (CMB), and mapping of millimeter-wave and submillimeter-wave emissions from interstellar dust and carbon monoxide (CO) over the entire sky. The CMB provides crucial information about the formation of galaxies and geometry of the universe. The Planck sky maps have been used to constrain other measurements of the so-called B-mode signal, an imprint of gravitational waves predicted by the theory of cosmic inflation.

2009
TacSat-3 spacecraft. The Advanced Responsive Tactically Effective Military Imaging Spectrometer (ARTEMIS) with MDL-fabricated gratings delivered processed information to the warfighter on the ground within 10 minutes, following a single-pass collection opportunity on a specified target.

2010
SOFIA (Stratospheric Observatory for Far Infrared Astronomy). MDL heterodyne receiver technology was used to map/detect unique interstellar molecular signatures with very high spectral resolution over a wide range of wavelengths.

2010
Carnegie Airborne Observatory (CAO) and National Ecological Observatory Network (NEON). Instruments with MDL-fabricated micromachined slits and e-beam-fabricated triple-blaze convex gratings addressed a need for macroscale measurements that reveal the structural, functional, and organismic composition of Earth's ecosystems.

2010–2012
Balloon-borne Large Aperture Submillimeter Telescope (BLAST). MDL-fabricated spider-web bolometer arrays observing simultaneously at 250, 350, and 500 μm imaged the sky to study the role played by magnetic fields in the star formation process.

2011
Mars Science Laboratory. MDL-fabricated tunable diode lasers in the tunable laser spectrometer–Sample Analysis at Mars (TLS-SAM) instrument suite established background levels of methane on Mars and showed that an additional unknown localized source is episodically producing methane plumes.

2012
MICA (Magnetosphere Ionosphere Coupling in the Alfvén Resonator) sounding rocket. An MDL-processed, low-voltage delta-doped CCD array for auroral electron detectors studied aurorae.

2012–2014+
Airborne Visible Infrared Imaging Spectrometer next generation (AVIRISng). Integrated MDL-fabricated slits, curved gratings, and QWIP focal plane arrays in the hyperspectral thermal emission spectrometer (HyTES) instrument are providing improved performance and the acquisition of contiguous spectral measurements between 380 and 2510 nm for use by a range of terrestrial ecology science investigations.

2014
SPIDER balloon-borne experiment. MDL-fabricated filters, antenna components, and transition-edge sensor (TES) arrays at 150 GHz and 90 GHz measured CMB polarization to search for the signature of primordial gravity waves, expected remnants from the postulated epoch of Inflation.

2015
25th anniversary of successful operations and deliveries from the Microdevices Laboratory (MDL).

MDL provided e-beam fabricated public outreach signature chips with thousands to millions of names and images to numerous flights: Space Shuttle STS-37 – 1991; Stardust – 1999; Mars Exploration Rovers (MER) Spirit and Opportunity – 2003; Spitzer Space Telescope – 2003; Dawn – 2007; Aquarius – 2011; Mars Science Laboratory (MSL) Curiosity rover – 2011; and Orion spacecraft test flight – 2014. Also, an e-beam-fabricated documentation package for the RADMON experiment was placed on the deck of the Mars Pathfinder lander – 1996.

LETTER FROM
CHARLES ELACHI & JONAS ZMUIDZINAS

THIS YEAR, JPL celebrates two major milestones: the 50th anniversary of Mariner 4's flyby of Mars—the first ever—and the 25th anniversary of our Microdevices Laboratory, or MDL. Surprisingly, there is a connection. In a recent article, Caltech professor Yuk Yung describes the scientific impact of the in situ detection of methane on Mars by the Curiosity rover: "If it is borne out, this discovery becomes one of the greatest Eureka moments in the half century of robotic exploration of Mars, beginning with the first success of Mariner 4 in 1965…" The detection was reported by MDL Director Chris Webster in a 2015 paper published in *Science*, and was enabled by a tunable infrared laser developed and produced at MDL by the group led by MDL Deputy Director Siamak Forouhar.

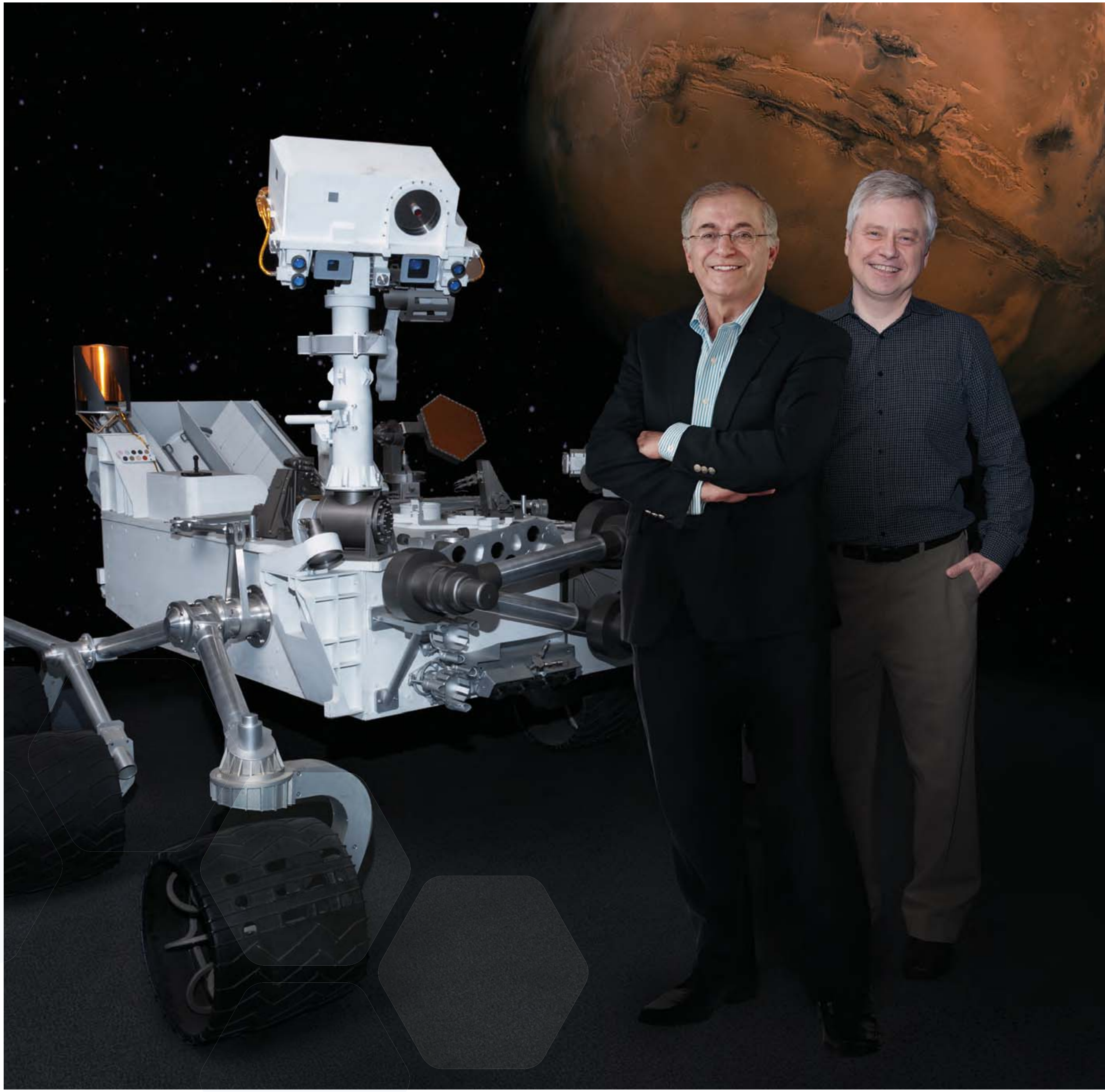
As with many triumphs in science, there is a long history. The basic technique of tunable infrared laser spectroscopy is almost as old as Mariner 4, and even before Mariner 4's Mars flyby, Carl Sagan was interested in the use of infrared spectroscopy to look for molecules in the Martian atmosphere. Thus, the scientific opportunity was apparent quite early but the technological and engineering challenges were daunting. The Mariner 4 radio science experiment told us the pressure of the Martian atmosphere and therefore the severe difficulty of landing, which prompted a host of clever solutions involving heat shields, parachutes, airbags, and ultimately Curiosity's skycrane, which amazed us all on the evening of August 6, 2012. Yet the task of making an infrared laser suitable for Mars was no less challenging—the starting point was a device cooled by liquid helium in a meter-sized cryostat. A major breakthrough was Rui Yang's 1995 invention of a new concept, the interband cascade laser (ICL), which uses an ingenious, complex, layered semiconductor structure to boost efficiency and reach much higher operating temperatures. Yang came to JPL/MDL to develop ICLs for Mars and received the 2007 Ed Stone Award for his work before joining the faculty at the University of Oklahoma. Today, room-temperature ICLs are being commercialized for detecting gas leaks and for in situ measurements of greenhouse gases.

This long history—25 years of work at MDL and 50 years of robotic exploration of Mars—serves to emphasize the difficulty of the challenges we undertake. Indeed, as John F. Kennedy said in his famous 1962 speech, we choose to do these things "not because they are easy, but because they are hard." We seek out important challenges for which there is a significant risk of failure, a risk of being seriously disappointed after a decade or more of very hard work. Yet we persist, because the challenges and the goals we pursue invigorate and motivate us in ways that lesser challenges would not.

Congratulations to all who have contributed to the success of the Microdevices Laboratory. The MDL has certainly made its mark in its first 25 years—may the next 25 be equally productive!

Dr. Charles Elachi
JPL DIRECTOR

Dr. Jonas Zmuidzinas
JPL CHIEF TECHNOLOGIST



Twenty-five years ago, the Microdevices Laboratory (MDL) was founded at JPL under the auspices of the Center for Space Microelectronics Technology (CSMT). NASA and several DoD agencies with space responsibilities established CSMT to create a critical-mass program in space microelectronics with world-class facilities, equipment, and staff.

CELEBRATING 25 YEARS OF SPECTACULAR SCIENCE

THE CREATION of the Microdevices Laboratory (MDL) was initiated 25 years ago in response to Caltech's Board of Trustees earlier request to the NASA Associate Administrator for Space Sciences, Dr. Burt Edelson, to consider new areas—other than robotic exploration—in which JPL could take lead responsibility for NASA. JPL Director Dr. Lew Allen and Chief Technologist Dr. Terry Cole then created the Center for Space Microelectronics, appointing Dr. Carl Kukkonen as its first Director. The rest is technological history. No one could have predicted the enormity of impact that MDL technologies would have on NASA Earth and space science mission successes, and in the areas of commercial applications, industry, healthcare, and national security.

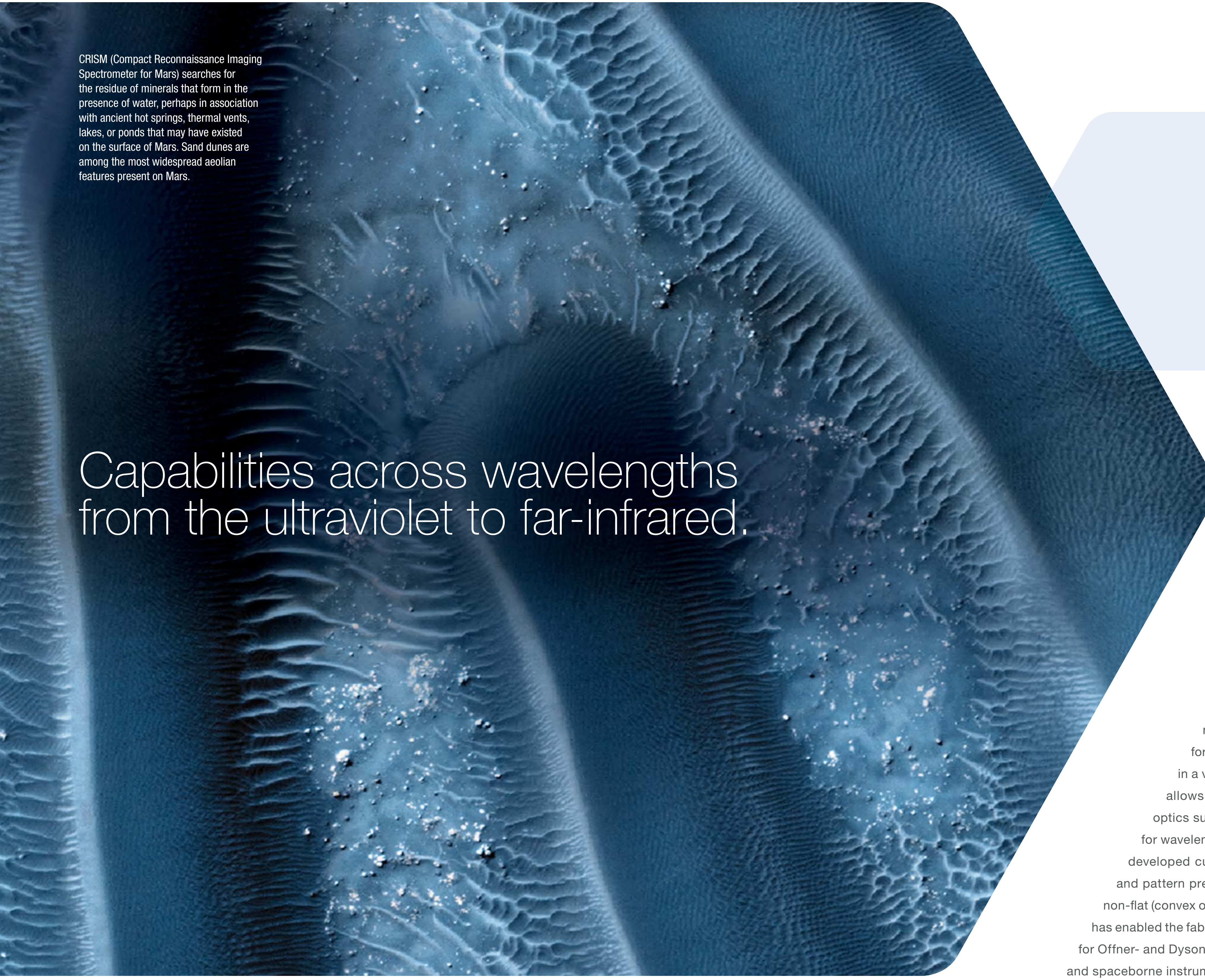
The vision for MDL was simple—build a state-of-the-art facility and hire world-class researchers with a free rein to conduct fundamental research in addition to targeting future NASA needs. As expected, the first five years were an investment in developing capability, acquiring new skills and equipment, and a rapid acquisition of technical know-how by an extremely capable team. Key new endeavors were born in superconducting detectors, infrared imaging, submillimeter devices, and quantum computing so that by the second five years an explosion of flight demonstrations was underway.

For the NASA space missions, we are proud to recall the incredible science results. The e-beam capability in diffractive optics allowed the CRISM instrument on the Mars Reconnaissance Orbiter to map carbonates, clays, and sulfates on Mars and help select a landing site for Curiosity. Then, MDL created tailored gratings that mapped lunar minerals and detected surface water using the M3 instrument on India's Chandrayaan-1 mission. Spider-web bolometers on the Herschel mission's SPIRE revealed thousands of new distant galaxies and witnessed a massive gas cloud from the red hypergiant fueling the interstellar medium. On the Planck mission, spider-web bolometers on HFI mapped dust and the cosmic microwave background (CMB), revealing the partitioning of energy and matter and providing a cornerstone of cosmological models for the next decade. More recently, superconducting detector arrays in a ground telescope at the South Pole have detected changes in B-mode polarization of the CMB that may provide the first evidence of rapid expansion following the Big Bang. On the Diviner instrument of the Lunar Reconnaissance Mission, microthermopile arrays were used to sense extremely low temperatures (38 K) in the permanently shadowed regions of craters on the Moon that could be cold-traps for organic material delivered by comets and other primitive bodies. Submillimeter-wave technologies developed at MDL have been used on a variety of space missions, beginning with the Earth-orbiting Microwave Limb Sounder on Aura that, by mapping numerous chemical species together, revealed the detailed mechanisms of ozone hole formation and dissipation over a decade of study. Advancement in this submillimeter technology allowed Herschel's HIFI instrument to measure the deuterium/hydrogen (D/H) ratio on comet Hartley 2 and thereby identify Jupiter-family comets as potential sources of Earth's water. The last decade has seen spectacular science discoveries from semiconductor laser development, including the discovery by the tunable laser spectrometer on Curiosity of methane emissions, the partitioning of the isotopes of carbon dioxide that establish a long history on Mars of atmospheric loss, and the first in situ measurement of D/H in a Martian rock. Lasers custom-made for Harvard University to target water isotopes on Earth have mapped the connection between stratospheric water injection and ozone loss. Not only have room temperature barrier infrared detectors made huge advances for national security, and single-photon detectors enabled laser optical communications, but MDL detectors at infrared, visible, and ultraviolet wavelengths have been used to unravel the mechanisms of the solar wind interaction with Earth's magnetic field, volcanic activity, wildfire spread, urbanization, and evapotranspiration. At Earth's ocean floor, our MDL electrophoresis microfluidic technology has detected long-chain fatty acids as biomarkers of localized microbial ecosystems.

Over the next 25 years, MDL will make unimaginable contributions to our national efforts in space, defense, and security—contributions that are inspired and made a reality by our world-class research staff who, along with management, take great pride in the pursuit of technical excellence and innovation. With NASA and Caltech, JPL Director Dr. Charles Elachi and Chief Technologist Dr. Jonas Zmuidzinas, we join our university, industrial, defense, and commercial partners in celebrating our incredible achievements over the last 25 years across a diverse range of applications. Our trademark and inspiration for the future remain in creative innovations in miniaturized technologies that contribute to the national interest.

Dr. Christopher Webster
DIRECTOR
JPL Microdevices Laboratory

Dr. Thomas S. Luchik
MANAGER
JPL Instruments Division



CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) searches for the residue of minerals that form in the presence of water, perhaps in association with ancient hot springs, thermal vents, lakes, or ponds that may have existed on the surface of Mars. Sand dunes are among the most widespread aeolian features present on Mars.

Capabilities across wavelengths from the ultraviolet to far-infrared.

> “A variety of **JPL flight missions** and **research projects** rely on our capability to fabricate special-purpose components for NASA and non-NASA instruments.”

DAN WILSON
Lead,
Diffractive Optics

20 YEARS AT JPL

Optical COMPONENTS

THE MICRODEVICES LABORATORY develops electron-beam lithography techniques to fabricate unique nanostructures and optics that enable JPL instruments to perform novel measurements and achieve unmatched performance. A variety of JPL flight and research projects rely on our capability to fabricate special-purpose components for NASA and non-NASA instruments. We have developed nano patterning processes for fabricating both binary-layered and grayscale surface-relief structures in a variety of polymers, dielectrics, metals, and substrate materials. This allows creation of nearly arbitrary transmissive and reflective diffractive optics such as blazed gratings, lenses, and computer-generated holograms, for wavelengths ranging from ultraviolet to long-wave infrared. Further, we have developed custom e-beam calibration techniques, substrate mounting fixtures, and pattern preparation software to allow fabrication of these diffractive optics on non-flat (convex or concave) substrates with several millimeters of height variation. This has enabled the fabrication of high-performance convex and concave diffraction gratings for Offner- and Dyson-type imaging spectrometers that have been used for many airborne and spaceborne instruments. »

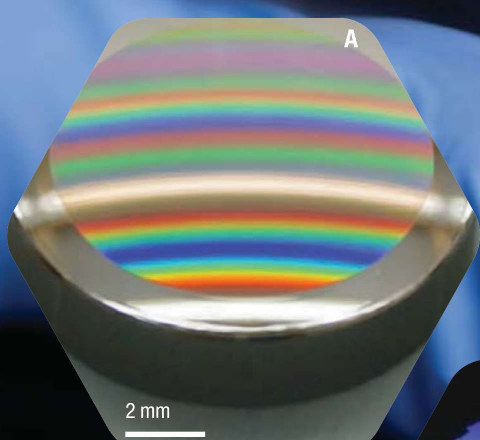
DIFFRACTION GRATINGS

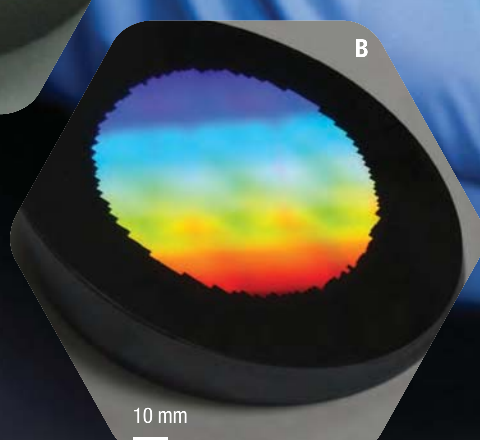
for Extreme Environments & Expanded Wavelength Operation

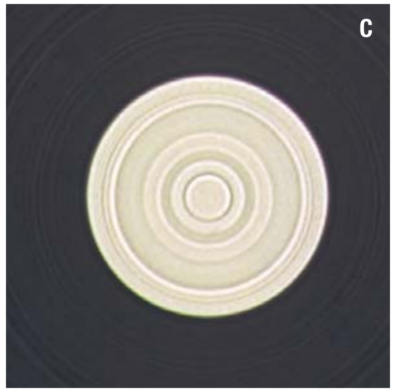
JPL'S IMAGING SPECTROMETER instruments are being developed for operation in a variety of high-radiation space environments, including Europa. Such instruments must also go through high-temperature thermal cycles for planetary protection. To provide flight-qualified gratings for these instruments, we have developed and qualified new processes that allow us to e-beam fabricate our high-performance, shaped-groove diffraction gratings in durable radiation-hard polymers and substrate materials.

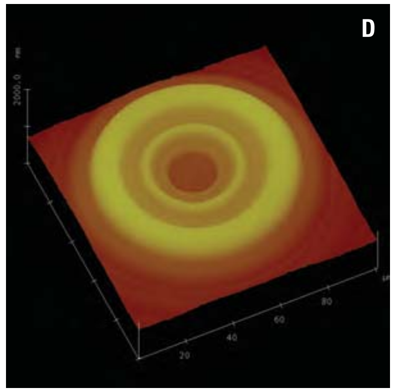
In addition, we are developing gratings for ultraviolet and high-resolution infrared spectrometers that require very fine pitch blazed grooves with extreme placement precision. This combination of requirements pushes the limits of electron-beam lithography, especially when writing on convex or concave substrates. This year, we successfully demonstrated such gratings, enabling the next generation of more compact and higher performance ultraviolet through long-wave infrared imaging spectrometers. ■

To address the need for larger computer-generated holograms (CGHs) than are available from commercial sources, MDL developed new electron-beam lithography capability to fabricate CGHs up to 9-inch diameter with pattern placement accuracy in the tens of nanometers.









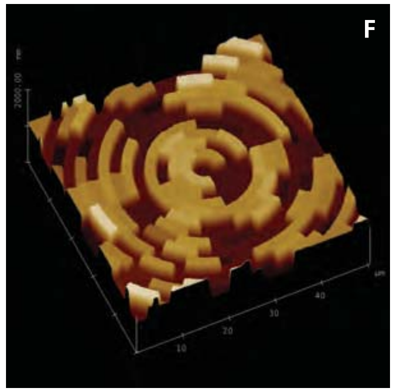


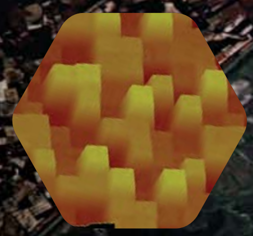
IMAGE A: E-beam-fabricated blazed convex grating (12 mm diameter) for an ultraviolet Offner imaging spectrometer. **IMAGE B:** E-beam-fabricated blazed immersion grating (55 mm diameter) etched into an infrared transmissive silicon prism for a high-resolution, wide-field imaging spectrometer for atmospheric gas measurement. **IMAGE C–D:** Microscope photo and atomic force microscope surface profile of an e-beam-fabricated occulting mask for the AFTA hybrid Lyot coronagraph (HLC). **IMAGE E–F:** Microscope photo and atomic force microscope surface profile of an e-beam-fabricated occulting mask for the phase-induced amplitude apodization complex mask coronagraph (PIAACMC).

CORONAGRAPH OCCULTING

Masks for the WFIRST-AFTA Mission

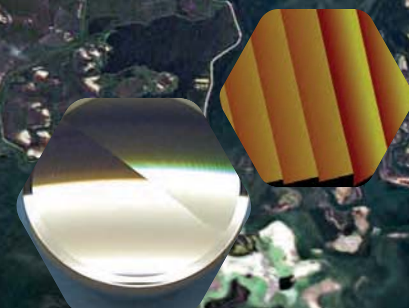
JPL IS DEVELOPING coronagraph technology to enable direct imaging and spectroscopy of exoplanets using the Astrophysics Focused Telescope Assets (AFTA) on the NASA Wide-Field Infrared Survey Telescope (WFIRST). MDL is developing techniques for fabricating two types of starlight-occulting masks, one for the hybrid Lyot coronagraph (HLC) design, and another for the phase-induced amplitude apodization complex mask coronagraph (PIAACMC) design. The HLC mask is a circular metal spot with a precisely aligned grayscale e-beam profiled dielectric pattern on top. The PIAACMC mask is an array of circular sections with precisely designed grayscale depths. Both types of masks work in conjunction with the rest of their respective coronagraph optics to suppress the light of a star by nearly 10 orders of magnitude to enable direct imaging and spectroscopy of the star's exoplanets and debris disk. After an initial process development phase, we successfully fabricated, precisely characterized, and delivered prototypes of both types of masks to the JPL coronagraph teams for optical performance evaluation. ■

PAST 25 YEARS
E-beam Highlights

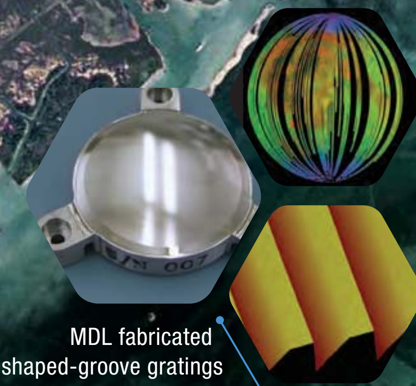


JEOL JBX-5DII
MDL's first e-beam tool was installed.

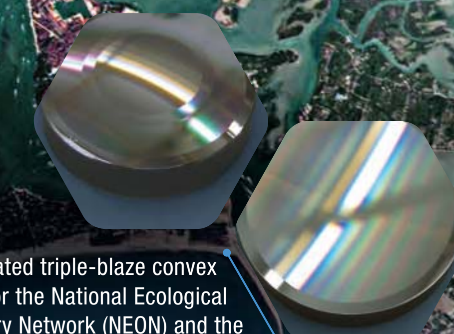
MDL developed novel grayscale e-beam lithography techniques for fabricating three-dimensional surface relief profiles in e-beam resist. This enabled precise fabrication of general diffractive optical elements, including high-efficiency blazed gratings.



MDL fabricated two convex dual-blaze flight gratings for the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)—still operational aboard Mars Reconnaissance Orbiter (MRO).



MDL fabricated shaped-groove gratings for Moon Mineralogy Mapper, which flew aboard the Chandrayaan-1 spacecraft.

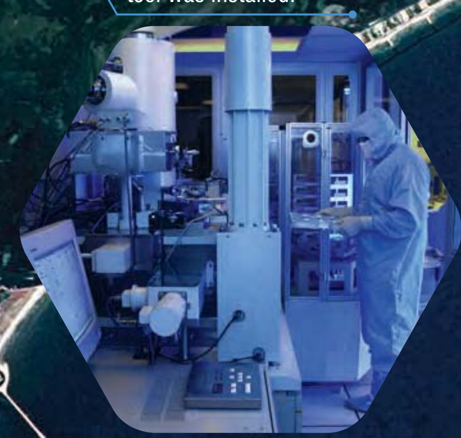


MDL fabricated triple-blaze convex gratings for the National Ecological Observatory Network (NEON) and the Carnegie Airborne Observatory (CAO).

’89 ’90s ’96 ’00 ’03 ’04 ’06 ’09 ’10 ’12

At the request of JPL imaging spectrometer designers, MDL developed e-beam techniques for fabricating our blazed gratings on convex spherical substrates. This enabled demonstration of high-efficiency, very-low-distortion Offner imaging spectrometer designs. MDL fabricated our first space-qualified convex grating and it was integrated into and flew in the Hyperion spectrometer (aboard the Earth Observing 1 satellite).

JEOL JBX-9300FS
JPL's second e-beam tool was installed.



Utilizing JPL R&TD funding, MDL developed shaped-groove grating technology. We developed groove-design algorithms that enable a grating to produce tailored spectral efficiency that equalizes a spectrometer's signal-to-noise ratio over a very broad multi-octave wavelength range.

MDL fabricated our first flight-qualified, shaped-groove grating for the ARTEMIS spectrometer (flew aboard TacSat-3 Earth-orbiting satellite), a collaborative effort between JPL and Raytheon.

MDL fabricated concave long-wave infrared gratings for the Hyperspectral Thermal Emission Spectrometer (HyTES)—still flying airborne campaigns.

MDL designed and fabricated a shaped-groove, low-polarization concave grating for the Portable Remote Imaging Spectrometer (PRISM).

A narrow barrier island protects the Lagoon of Venice from storm waves in the northern Adriatic Sea, and breakwaters protect inlets to the lagoon. Red tiles on the roofs of Venice contrast with the grays of the sister city of Mestre, and the cities are joined by a prominent causeway.

Using the MDL-developed IC laser at 3.27μm, TLS detected methane on Mars.

A Martian dust devil roughly 12 miles (20 km) high was captured winding its way along the Amazonis Planitia region of northern Mars on March 14, 2012, by the High-Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter. Despite its height, the plume is little more than three-quarters of a football field wide.

"Pioneering MDL work in semiconductor lasers has enabled a new era of **laser spectroscopy for space.**"

SIAMAK FOROUHAR
Lead, *Semiconductor Lasers and Optoelectronics*

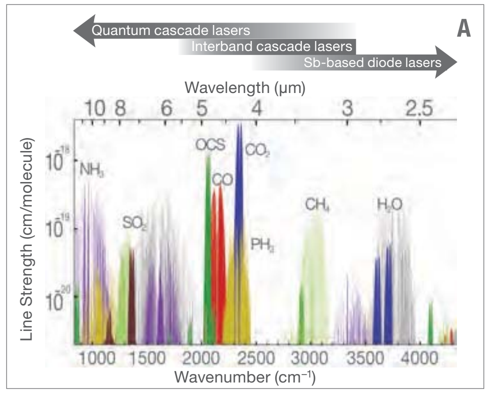
28 YEARS AT JPL

Semiconductor LASERS

OVER the last two decades, semiconductor lasers have improved in performance to above-room-temperature operation with high output power (tens of milliwatts), low power consumption (less than a watt), and cover a wide range of wavelengths. Due to these advancements, tunable laser spectrometers have become the instrument of choice for precise measurements of gas abundances and their isotope ratios in Earth and planetary gases, arising from either the atmosphere or evolving from rock pyrolysis.

During the years of MDL's existence, we have put in place all the necessary infrastructure and expertise required to design, fabricate, and space qualify semiconductor lasers. Today, MDL specializes in custom development and space qualification of a wide range of semiconductor laser, i.e., diodes, interband, and intersubband quantum cascade (QC) designs, made from a variety of material systems including gallium arsenide, gallium antimonide, and indium phosphide for wavelengths ranging from 1.0 to 10 μm.

Within the last year, MDL developed and delivered record high output power interband cascade (IC) lasers emitting in the 3.0–3.5 μm wavelength range, enabling the first applications of integrated cavity output spectroscopy (ICOS) instruments to study the chemistry of key halogens (such as HCl and ClO) in the stratosphere and cavity ring-down spectroscopy (CRD) instruments for detection of ethane at ppb levels. »



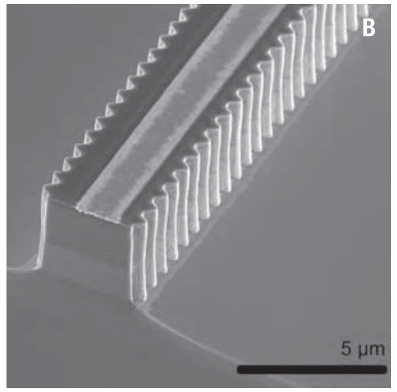


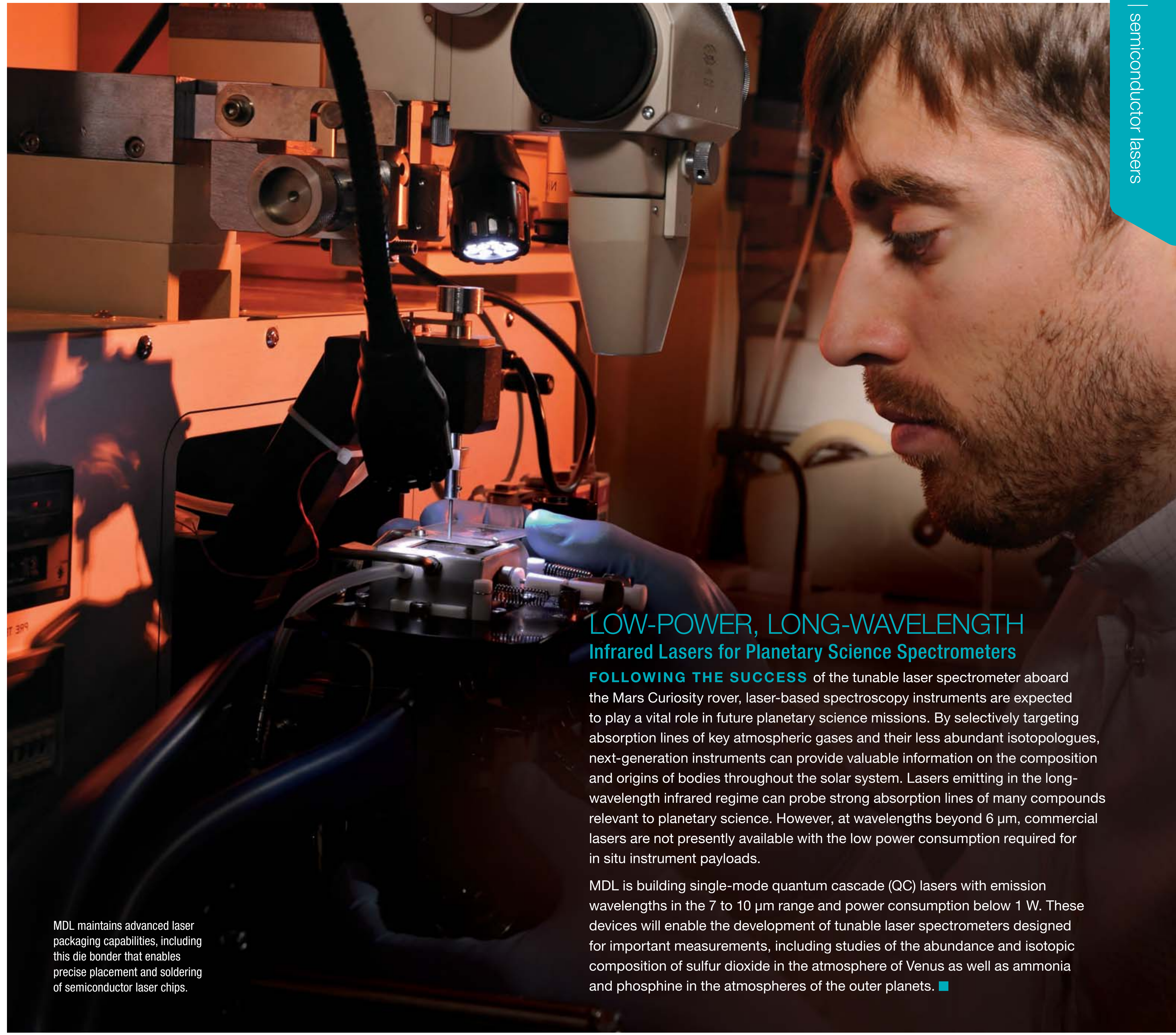
IMAGE A: Several infrared absorption features of interest in planetary science and environmental monitoring are shown in comparison to the capabilities of existing infrared laser technologies. **IMAGE B:** Scanning electron micrograph of a sidewall-grating distributed-feedback QC laser fabricated at MDL. **IMAGE C:** 1 mm x 0.5 mm QC laser chips produced at MDL. The lasers are soldered into a temperature-controlled package for integration with laser spectroscopy instruments. **IMAGE D:** A semiconductor QC laser wafer processed in the MDL cleanroom. After cleaving into individual devices, this small section will produce more than 100 individual lasers.

LASER-BASED SENSORS

for Environmental Monitoring and Spacecraft Fire Safety

MDL IS DEVELOPING combustion product monitoring instruments to address manned spacecraft fire safety for future NASA missions. Using semiconductor lasers to probe molecular absorption lines at infrared wavelengths, these instruments provide a real-time record of ambient gas concentrations with remarkable sensitivity and specificity. Laser-based sensors sniff out the slightest increase in the levels of poisonous gases generated by accidental fires with rapid response time and long-term measurement stability.

The latest JPL instrument pictured below simultaneously monitors ambient levels of CO, HCl, HCN, HF, and CO_2 using mid-infrared lasers fabricated in the MDL cleanroom facility. Using this five-channel sensor, the target gases are detected at the parts-per-million level. Looking ahead to interplanetary manned spaceflight missions, it will become even more critical to provide astronauts with exceptionally accurate combustion sensors capable of long-duration, service-free operation. ■



MDL maintains advanced laser packaging capabilities, including this die bonder that enables precise placement and soldering of semiconductor laser chips.

LOW-POWER, LONG-WAVELENGTH

Infrared Lasers for Planetary Science Spectrometers

FOLLOWING THE SUCCESS of the tunable laser spectrometer aboard the Mars Curiosity rover, laser-based spectroscopy instruments are expected to play a vital role in future planetary science missions. By selectively targeting absorption lines of key atmospheric gases and their less abundant isotopologues, next-generation instruments can provide valuable information on the composition and origins of bodies throughout the solar system. Lasers emitting in the long-wavelength infrared regime can probe strong absorption lines of many compounds relevant to planetary science. However, at wavelengths beyond 6 μm, commercial lasers are not presently available with the low power consumption required for in situ instrument payloads.

MDL is building single-mode quantum cascade (QC) lasers with emission wavelengths in the 7 to 10 μm range and power consumption below 1 W. These devices will enable the development of tunable laser spectrometers designed for important measurements, including studies of the abundance and isotopic composition of sulfur dioxide in the atmosphere of Venus as well as ammonia and phosphine in the atmospheres of the outer planets. ■

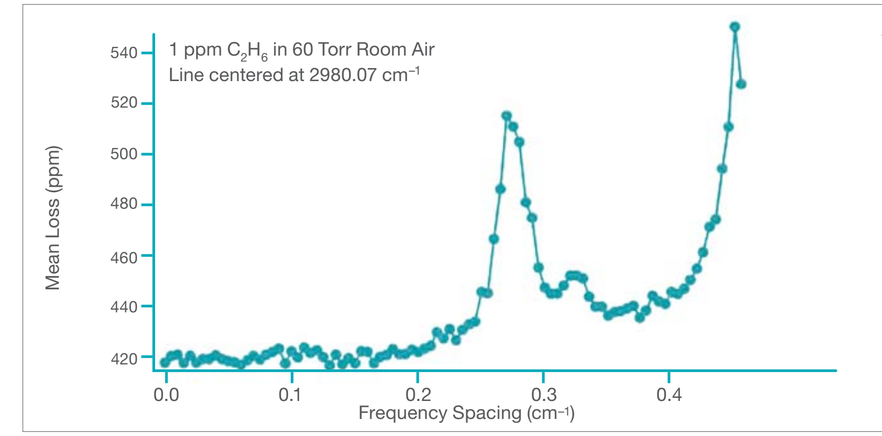
MID-IR LASERS FOR HIGH

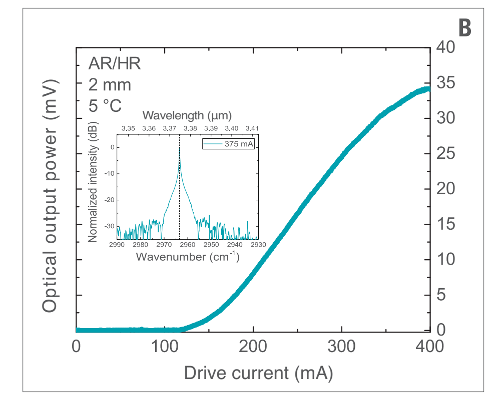
Ultra-Precision Spectroscopy Instruments

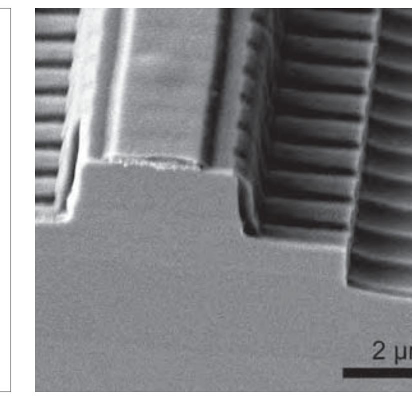
MDL LASERS HAVE ENABLED measurements of greenhouse gases, their isotopes, and reactive intermediates in the troposphere and the stratosphere (OH, H_2O, HDO, CH_4, HCl, and C_2H_6) on the order of parts-per-trillion (ppt) concentrations via integrated cavity output spectroscopy (ICOS) and cavity ring-down spectroscopy techniques. Tunable laser absorption spectroscopy (TLAS) is a versatile and robust method for gas sensing with applications ranging from industry to Earth and planetary science. Together with techniques such as wavelength-modulation spectroscopy, TLAS with simple absorption cells is capable of detection limits on the order of parts per million, which is sufficient for many applications of interest. However, for weaker-absorbing molecules or measurements that require higher sensitivity, a cavity-enhanced method, such as cavity ring-down spectroscopy, is often used and requires light sources capable of emitting tens of milliwatts of single-mode power due to the low coupling of the light into a high-finesse cavity. In collaboration with the epitaxial growth expertise of Naval Research Laboratory and MDL's semiconductor laser fabrication expertise, JPL has delivered high-power interband cascade lasers emitting at 3.38 µm for integration in Harvard Professor Anderson's ICOS instrument and Caltech Professor Okumura's cavity ring-down spectrometer. Professor Anderson's research is focused on investigating the relationship between climate change and stratospheric ozone depletion at mid-latitudes by measuring ppt levels of HCl and HDO, while Professor Okumura's spectrometer targets fugitive natural gas emissions such as ethane to determine if the shift towards natural gas energy production exacerbates climate change. The technological accomplishment of MDL lasers has enabled cutting-edge science. **Ultimately, the lasers developed at MDL have bridged the long-standing gap in commercially available laser technologies and have enabled state-of-the-art spectroscopy techniques for atmospheric science.** ■

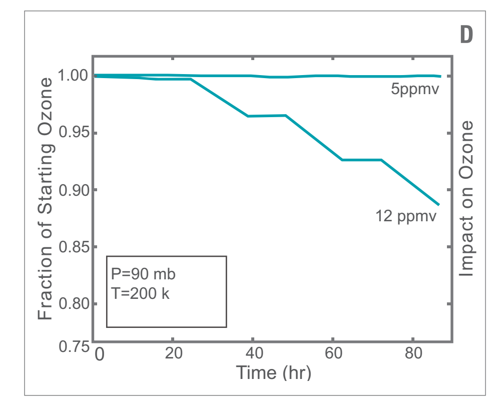
NASA's ER-2 high-altitude Earth science aircraft is used for environmental science, atmospheric sampling, and satellite data verification missions. Harvard Professor Anderson has a history of using this aircraft for stratospheric measurements in his research.

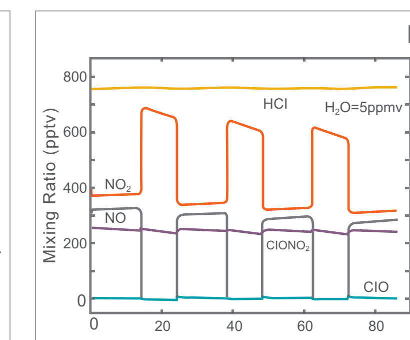
CREDIT: NASA Photo/Tony Landis











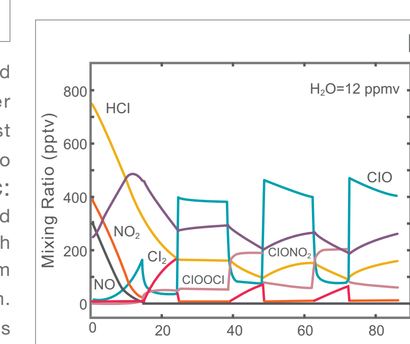
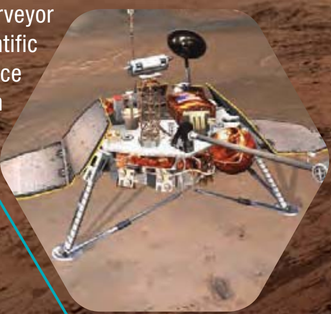


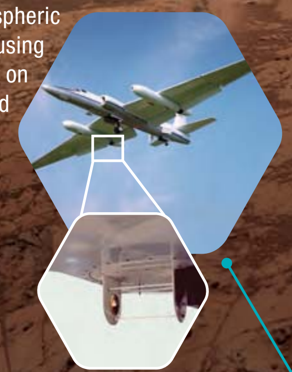
IMAGE A: Absorption spectra of ethane measured with Caltech's cavity ring-down tunable laser spectrometer using an MDL laser. This is the first time a semiconductor laser has been used to measure ethane via cavity ring-down. **IMAGE B–C:** Electron micrograph of a double-ridge interband cascade laser with a lateral Bragg grating with corresponding output power and spectrum designed for single-frequency emission at 3.38 µm. **IMAGE D–F:** Calculations by Professor Anderson's group showing how warmer surface temperatures can lead to a wetter and cooler stratosphere, which can lead to ozone loss at mid-latitudes. Anderson, J. G., et al. (2012), "UV Dosage Levels in Summer: Increased Risk of Ozone Loss from Convectively Injected Water Vapor," *Science*, 337 (6096), 835–839 [DOI:10.1126/science.1222978].

SEMICONDUCTOR LASERS

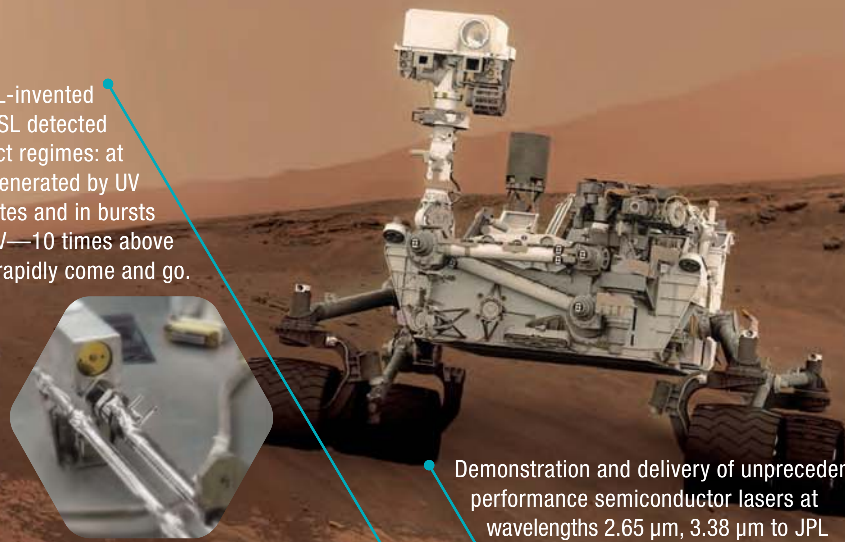
Have Enabled a New Era of Laser Spectroscopy That Can Make Precise Measurements of Gas Abundance and Their Isotope Ratios in Earth and Planetary Gases



The Mars Volatiles and Climate Surveyor (MVACS) is an integrated scientific payload containing a Stereo Surface Imager, robotic arm, robotic arm camera, meteorology package, and a Thermal and Evolved Gas Analyzer.



High-accuracy stratospheric water measurements using MDL 1.87-μm lasers on NASA's DC-8, ER-2, and WB-57F aircraft.



Mars methane detection: Using the MDL-invented IC laser at 3.27 μm, TLS-SAM on MSL detected methane on Mars in two distinct regimes: at background levels of 0.7 PPBV generated by UV degradation of infalling meteorites and in bursts of methane at 7 PPBV—10 times above background—that rapidly come and go.

Demonstration and delivery of unprecedented performance semiconductor lasers at wavelengths 2.65 μm, 3.38 μm to JPL scientists, Harvard University, and California Institute of Technology.

This work has revolutionized the application of integrated cavity output spectroscopy and cavity ring-down spectroscopy techniques for measurement of isotopes and reactive intermediates in the troposphere and stratosphere.

'92

Room-temperature InGaAs strained-layer lasers demonstrated beyond 1.7 μm.

Developed the world's first CW InGaAs strained-layer semiconductor laser in the 1.8–2.1 μm range.

'95

Delivery of space-qualified 2-μm lasers for Mars '98.

'96

Licensing and commercialization of the semiconductor laser technology by Spectrasensors, a leading global provider of laser-based on-line analyzers for process control and monitoring applications.

Delivery of space-qualified 1.37-μm laser for Deep Space 2 mission.

The first delivery of semiconductor lasers for tunable laser spectrometers on Mars: Mars Volatiles and Climate Surveyor and Deep Space 2.

'98

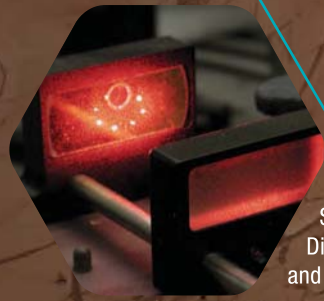
'00

Major capital equipment investment: GaSb MBE.

'04

Delivery of 1.87-μm lasers for balloon experiment.

Interband cascade lasers selected for Mars TLS.



Several proposals developed for Discovery missions to the Moon, Venus, and for Mars atmospheric probes.

'05

Demonstration of 250-K interband cascade laser at 3.27 μm.

'06

Developed and delivered the first interband cascade laser with the emission wavelength of 3.27 μm for detection of methane on Mars.

Pascal complete TDLS instrument with 1.87-μm laser diode inside.

'12

TLS successfully activated on Mars rover Curiosity.

'14

Broad-spectrum detectors for on-sky observation.

This Hubble image shows the spiral galaxy Messier 83, also known as the Southern Pinwheel Galaxy. In 2008, using UV images collected by the Galex spacecraft, astronomers discovered the birth of new stars in the spiral arms of Messier 83. At 15 million light-years from Earth, this galaxy has also presented many supernova explosions and may have a double nucleus at its core.

CREDIT: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)—William Blair (Johns Hopkins University).

> **"Our work is primarily** in high-performance ultraviolet/visible/near infrared and low-energy particle detector arrays, and the systems they enable."

SHOULEH NIKZAD
Lead, *Advanced Detectors, Systems and Nanoscience*

23 YEARS AT JPL

ADVANCED Detectors, Systems & Nanoscience

THIS YEAR MARKED an exciting period for MDL in advanced detectors, systems, and nanosciences. Solar-blind silicon detectors were demonstrated as delta-doped and superlattice-doped detectors with integrated filters, and advances were made with solar-blind devices based on GaN and its alloys. Delta-doped arrays will be on sky soon, as deliveries were made to Caltech Optical Observatories (COO) for use at the Palomar Observatory as well as the Steward Observatory on Mount Bigelow (Arizona State University). Deliveries for the Faint Intergalactic Redshifted Emission Balloon (FIREBall-2) and Colorado High-resolution Echelle Stellar Spectrograph (CHESS, a sounding rocket) are completed or are well underway, with first light and launch windows planned within the next year.

Delta doping was invented at JPL in 1992. Since then, delta doping has been applied to a multitude of device formats, and several patents have been granted for hybrid and monolithic UV/visible/NIR and other spin-off devices. Recent inventions such as superlattice doping, custom atomic layer deposition (ALD)–integrated antireflection (AR) coatings, and integrated visible-blind filters improve the performance and extend the range of applications while building on the success of the first delta-doped CCD demonstrated with 100% internal quantum efficiency (Hoenk et al., APL, 1992). Unprecedented performance combined with high-throughput, high-yield processing has been enabled by investment in a large-capacity, 8-inch silicon molecular beam epitaxy (MBE) system. This added infrastructure makes it possible for these high-performance arrays to be in the hands of astronomers, physicists, cosmologists, industrialists, and neurosurgeons. »

The effort that began with single die per week end-to-end production has now evolved to produce high-performance devices at a rate that can be affordable for incorporation into, for example, a 10-meter-aperture telescope UV/optical/IR Surveyor mission under study as well as Explorers, planetary missions, and suborbital missions. The effort has been expanded into developing coatings for optical components as well as creating compact, high-performance UV instruments (imaging and spectrometry) using JPL's advanced detection and dispersion components and system design. ■

KECK INSTITUTE for Space Studies Technology Development — Single-Photon-Counting Detectors

THE KECK INSTITUTE FOR SPACE STUDIES (KISS) funded a technology development program for next-generation ultraviolet instrument technologies. Under this program, MDL developed single- and multiple-layer antireflection (AR) coatings for integration with silicon-based detectors. Coatings are applied directly to the detector surface by ALD, which offers nanometer-scale control over film thickness and interface quality, allowing for precision growth of multilayer films. JPL will deliver 2-megapixel, delta-doped, AR-coated electron-multiplying CCDs (EMCCDs) for the FIREBall experiment designed to measure emission from HI, OVI, and CIV, all red-shifted to the stratospheric balloon window (195–215 nm). This combination results in a photon-counting detector with quantum efficiency (QE) > 70% at 205 nm, nearly an order of magnitude higher than the previously flown FIREBall-1 detector based on microchannel plate technology. ■

ON-SKY Observation with Broadband Detectors

MDL RECENTLY DEVELOPED and delivered broadband silicon CCD arrays for the Wafer Scale camera at Prime focus (WaSP) instrument, an upgrade to the current prime focus imager at Palomar Observatory's 200-inch Hale telescope. These dedicated 4-megapixel guide and focus CCDs are required to maintain both telescope tracking (during long exposures) and focus (during a night's observing). JPL's superlattice-doping technology combined with multilayer AR coatings prepared by ALD delivers enhanced blue sensitivity with high quantum efficiency optimized over 320–1000 nm. This is highly advantageous when observing through short-wavelength filters where suitable guide stars (for tracking and guiding) become faint and CCD throughput typically drops. These 2kx2k, 15-µm pixel deep-depletion CCD arrays are designed by STA and fabricated at Teledyne DALSA. Custom packaging and wire-bonding techniques were designed at JPL to meet the special needs of the WaSP instrument for a closely packed camera. ■

MDL uses atomic layer deposition to prepare single- and multi-layer thin films with subnanometer-scale precision. ALD allows fabrication of device-integrated antireflection coatings and filters, as well as robust protective coatings for stand-alone optics.

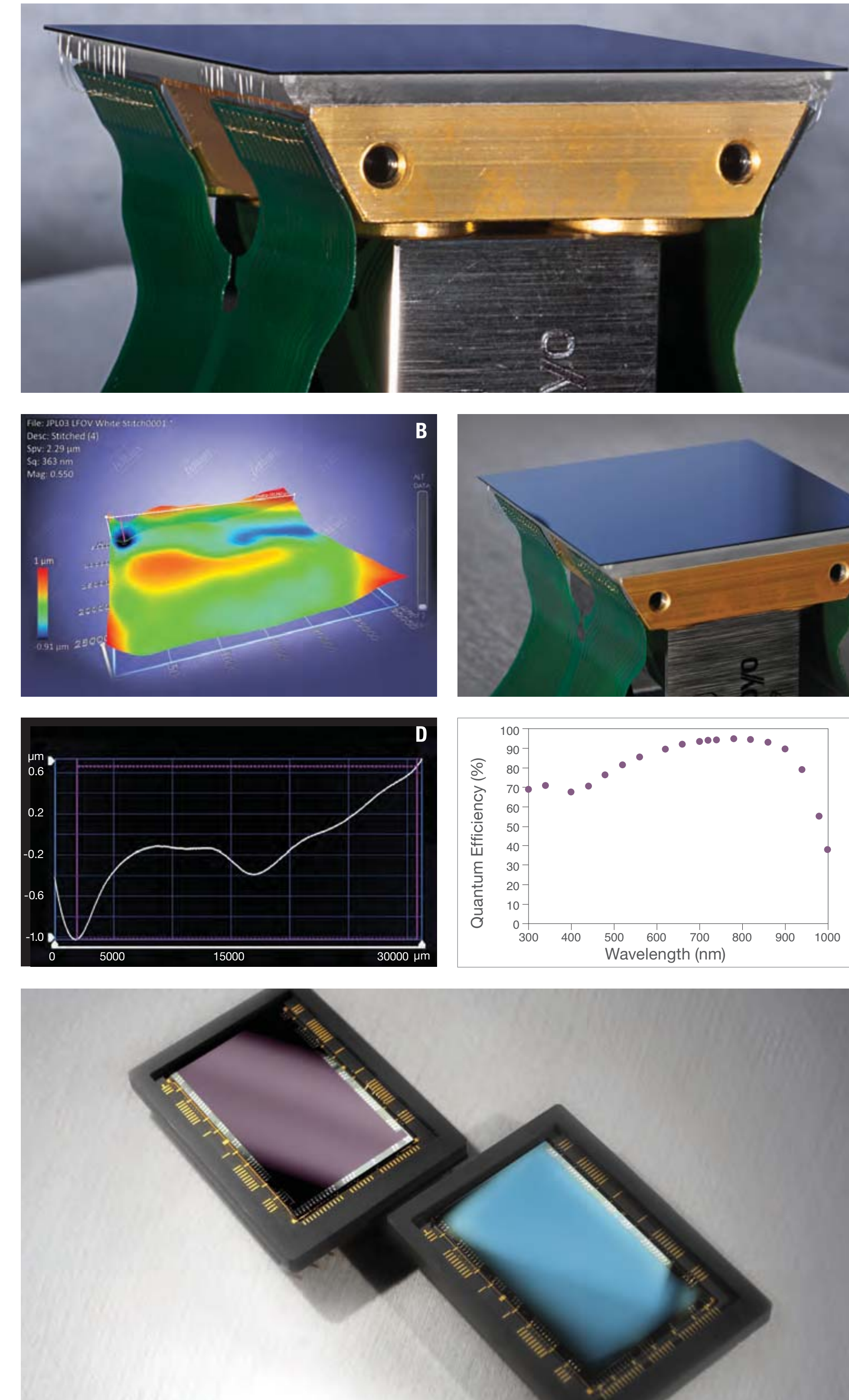
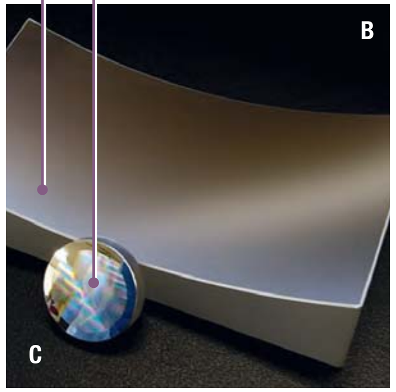


IMAGE A&C: Four-side buttable, ultraflat WaSP guide and focus CCD for Palomar. **IMAGE B&D**: The exceptional surface flatness of our detectors is measured in single µm. **IMAGE E**: The plot shows measured QE data for one of the superlattice-doped, AR-coated WaSP detectors (145 K). **IMAGE F**: Two packaged EMCCDs (e2v) that have been delta doped and AR coated for the FIREBall experiment. The different colors (dark purple and light blue) result from differences in the AR coating design.



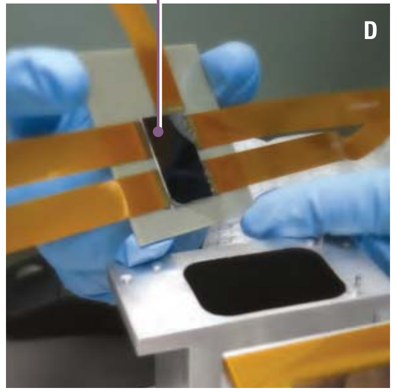
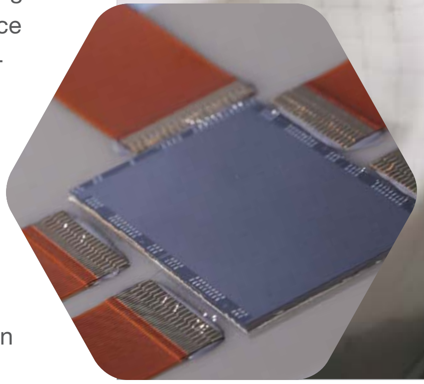


IMAGE A: Ultraviolet spectrometer prototype based on JPL's UV technologies. **IMAGE B**: The UVS mirror was prepared using advanced ALD coating technologies developed in MDL. **IMAGE C**: The convex grating for UVS was fabricated using electron beam on a curved substrate. Advanced ALD coatings ensure high performance well into the UV. **IMAGE D**: The delta-doped detector for JPL's UVS includes a customized AR coating deposited by ALD.

ULTRAVIOLET SPECTROMETER

Based on JPL's Ultraviolet Technologies

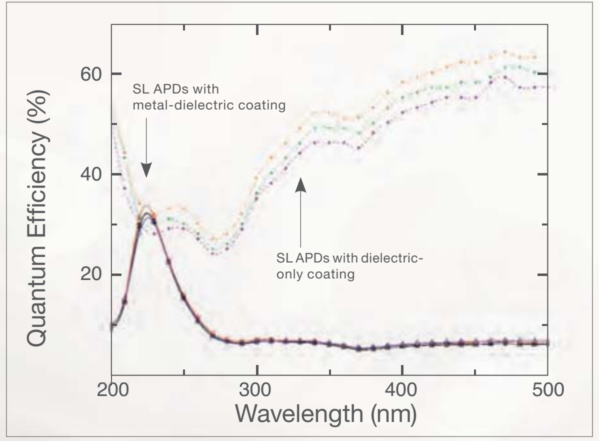
THE ULTRAVIOLET SPECTROMETER (UVS) project is part of the effort to create a compact, high-performance instrument utilizing several key technologies pioneered at MDL. The first technology is high-performance ultraviolet detectors using delta doping and superlattice doping developed at JPL. The second technology is electron-beam-fabricated gratings on curved substrate enabling compact and efficient optical designs such as a compact Offner imaging spectrometer. The third technology is in the development of tuned optical filters and coatings directly deposited on detectors as well as efficient, high-reflectivity coatings on optical surfaces such as spectrometer mirrors and gratings using ALD. This process enables finer control over spectral parameters and improved optical efficiency. The combination of these technologies in an Offner design is shown in the figure as a laboratory demonstration. ■



Solar-Blind Silicon and APPLICATIONS

ULTRAFAST SCINTILLATION DETECTORS are needed for fundamental scientific discoveries in particle physics and astronomy. Barium fluoride (BaF2) has the potential for detecting gamma rays with subnanosecond timing resolution; however, the fast scintillation of BaF2 at 220 nm is accompanied by a larger, slower component at 300 nm. MDL developed integrated interference filters on superlattice-doped avalanche photodiodes (APDs) to detect the 220-nm light while rejecting the 300-nm light when combined with a BaF2 scintillator. This project is a collaboration with Radiation Monitoring Devices (RMD) and physics Professor David Hitlin (Caltech), who brings extensive experience with scintillation detectors for high-energy physics experiments.

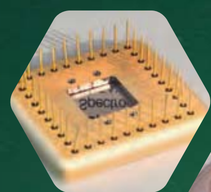
APDs offer high gain and the potential for single-photon counting as an alternate to image-tube devices. MDL demonstrated that superlattice-doped APDs have an order of magnitude faster response than standard APDs and are robust against irradiation with high-energy particles and photons. Our metal-dielectric coating enables the detector to achieve high QE at 220 nm, while rejecting out-of-band light. We have shown the rejection of out-of-band (300 nm) light with an unprecedented (for silicon) four orders of magnitude. For comparison, the response of superlattice-doped APDs with dielectric-only coatings does not exhibit this selective response (see plot below). ■

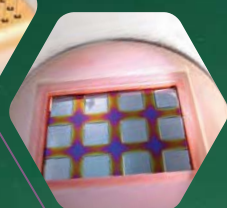


Installation of the assembled UVS prototype in a test chamber where it will undergo performance characterization. The prototype design allows individual components to be exchanged easily, permitting rapid development of the underlying technologies without costly redesigns.

MDL MILESTONES
Twenty-Five Years of Enabling Innovations

Background image: A delta-doped, frame-thinned Cassini imager is launched into the Aurora Borealis to measure charged particles (Poker Flats, Alaska).

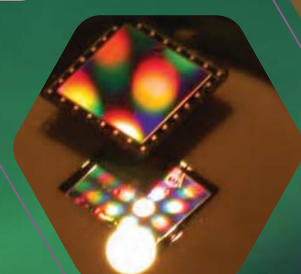




Production of flat membrane and supported imagers.

Isotopic resolution of low-energy molecular fragments using a delta-doped Cassini imager integrated with JPL's miniature mass spectrometer.

First spaceflight on Nike-Orion sounding rocket. The High-Altitude Ozone Measuring and Educational Rocket (HOMER) instrument suite included an advanced delta-doped CCD from MDL that measured the ozone concentration.



A flat Cassini imager (above) together with a curved Cassini imager (below). Work with curved arrays helped determine the fundamental limits of this detector format.

'92

Delta-doped CCD first demonstrated: a 100x100 pixel region is tested to have 100% internal QE.

'94

Delta-doping technology extended to 1kx1k detector format; demonstrated improved stability and uniformity.

'98

Demonstration of in-house die-level thinning with a 1kx1k, 12-µm-format Cassini imager. Production of flat-membrane and supported imagers.

'99

Demonstrated first curved focal plane array.

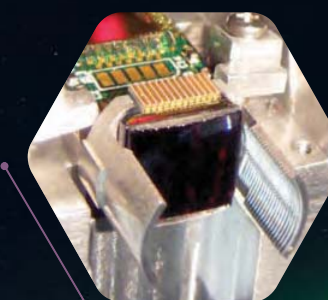
'02

'03

Record-breaking sensitivity to low- energy electrons demonstrated.

First demonstration of n-type delta doping, as well as successful hybridization of delta-doped imagers to CMOS ROIC.

'08



A 1-cm diagonal, delta-doped, CMOS micro-imaging array hybridized to a CMOS ROIC with 7000 indium bump bonds. A plano-convex lens is directly attached to the imager.

Johns Hopkins University flew a delta-doped CCD in the Long-Slit Imaging Dual Order Spectrograph (LIDOS) on three separate sounding rocket missions spanning 2003–2008. The UV-sensitive detector successfully returned data on several celestial objects.

'09

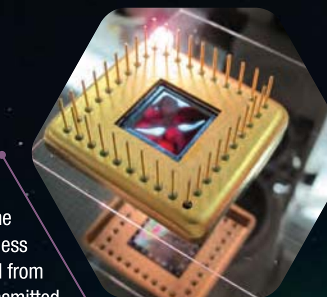
Acquisition of Veeco Gen200 MBE, with the capacity to process wafers up to 8 inches in diameter. Ultra-flat detector packaging developed for large-format arrays. End-to-end high-throughput processing of UV/VI/NIR scientific imagers.

Magnetosphere-Ionosphere Coupling in the Alfvén (MICA) sounding rocket flight of a delta-doped CCD array as the detector for a compact low-energy electron scattering (LEES) instrument.

'10

Successful demonstration of wafer-level delta doping for thick, high-purity wafers as well as bonded epi-layer wafers.

'11

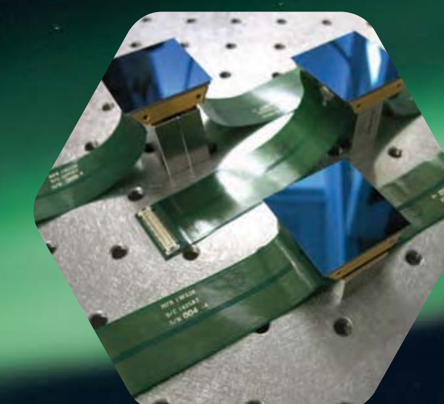


A frame-thinned Cassini imager shows the characteristic clover-like surface variations resulting from the device thickness being thinned to less than 20 µm. Red light reflected from the mirror surface below is transmitted through the thin membrane.

'12

Superlattice-doped detectors demonstrate unprecedented stability against damaging radiation. Successful demonstration of device-integrated antireflection coatings and bandpass filters prepared by atomic layer deposition.

'14



JPL developed four-side buttable packaging for mosaicked detectors that were delivered to Palomar Observatory. The 2kx2k, 15-µm-format detectors (STA) were delta doped and include device-integrated antireflection coatings deposited by ALD.

JPL developed a mid-infrared camera based on 256x256 quantum well infrared photodetector (QWIP) focal plane arrays. The camera is designed to operate from the prime focus of the Hale 200-inch (5-meter) telescope at Palomar with a wide 2'x2' field of view and diffraction-limited 0.5" pixels. QWICPIC is designed to observe at 8.5 and 12.5 μm simultaneously to map comparatively large regions of the sky in thermal dust emission or to survey highly confused regions for reddened embedded objects. The Hale telescope (f/3.3) was the world's largest effective telescope for 45 years (1948–1993).

Cutting-edge infrared photodetectors for space and terrestrial applications.

An 8.5-μm, mid-infrared image, obtained with a QWICPIC at the primary focus of the Palomar Observatory's Hale telescope, shows high-mass star-forming regions.

> **“JPL** is recognized as one of the world's leading institutions in **infrared detector technology** development.**”**

SARATH GUNAPALA
Director, *Center for Infrared Photodetectors*

23 YEARS AT JPL

Infrared PHOTODETECTORS

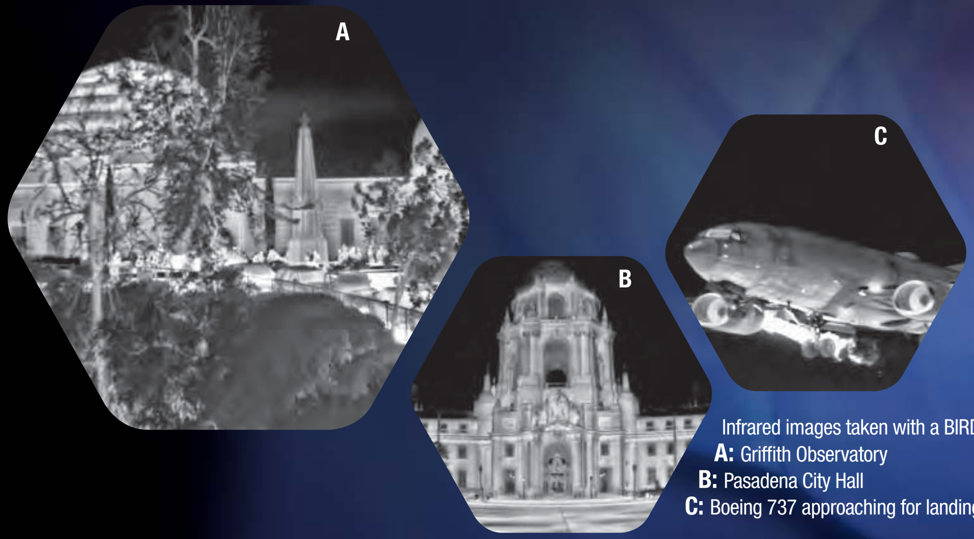
VISIBLE LIGHT SPANNING the wavelength range from blue to red is a tiny slice of the electromagnetic spectrum. While an enormous wealth of scientific information can be and is obtained through imaging and spectroscopy in visible light, the invisible portion of the spectrum can be harvested to yield both more detailed and new information. An object at room temperature and in complete darkness may be perfectly invisible to the human eye, but its temperature will make it glow in the infrared, shining brightest at infrared wavelengths. In the early nineties, JPL formed an MDL group to develop novel infrared detector technologies that can enable new observational instruments. MDL's comprehensive end-to-end capabilities include concept development, simulation and design of quantum structure devices, materials growth and characterization, array fabrication, and characterization of detector arrays. MDL has made numerous advances in infrared detection technology, including the high operating temperature barrier infrared detectors covering the entire infrared spectrum.In recognition of continuing work in this area, JPL created the Center for Infrared Photodetectors in 2031. »

COMPLEMENTARY BARRIER
Infrared Detectors (CBIRDs)

ONE OF THE LATEST devices MDL has developed based on superlattice heterostructure is known as the complementary barrier infrared detector (CBIRD). The CBIRD utilizes unipolar barriers to reduce the minority carriers in the absorber region through carrier exclusion and carrier extraction. This allows the CBIRD to operate below the equilibrium minority carrier level and at higher operating temperature (HOT). The CBIRDs cover the mid-wavelength IR (MWIR), long-wavelength IR (LWIR), and very-long-wavelength IR (VLWIR) spectral regions with high quantum efficiency and diffusion-limited dark current. The antimonide-based superlattice CBIRDs are grown on low-cost 100 mm GaSb substrates. CBIRD technology has already demonstrated a clear path for low-cost, high-pixel-operability, highly uniform, high-performance HOT infrared focal plane arrays for applications in MWIR, LWIR, and VLWIR spectral regions. ■

HIGH-RESOLUTION IR IMAGERS
for Planetary Missions

BOTH VENUS AND SATURN'S MOON TITAN have thick, opaque atmospheres that prevent imaging of their surfaces at most visible and near-infrared wavelengths. Following the Venus Express and the Cassini–Huygens missions, it is now known that both of these atmospheres have "windows" at specific wavelengths where the surface is viewable. A high-resolution imaging system with sensitivity in these key infrared wavelengths would be a powerful technique for resolving planetary surface features beneath optically thick atmospheres. It would also be capable of probing different depths in giant planet atmospheres, and could provide infrared color (i.e., composition) information on airless bodies. This imaging system therefore has wide applicability to NASA's planetary missions, in addition to Titan and Venus specifically. The BIRDs offer numerous potential advantages over existing detector technology including low dark current, broad spectral coverage, and high quantum efficiency. In particular, BIRD detectors exhibit very low 1/f noise and high temporal stability, thus enabling long integration times and eliminating frequent calibrations. BIRD technology offers robust manufacturability and lower development cost. The recent progress in BIRD technology, including demonstration of large-format, small-pixel-pitch MWIR and LWIR FPAs, clearly demonstrates that this technology has reached the maturity level required for infusion into planetary instruments. ■



Infrared images taken with a BIRD camera:
A: Griffith Observatory
B: Pasadena City Hall
C: Boeing 737 approaching for landing

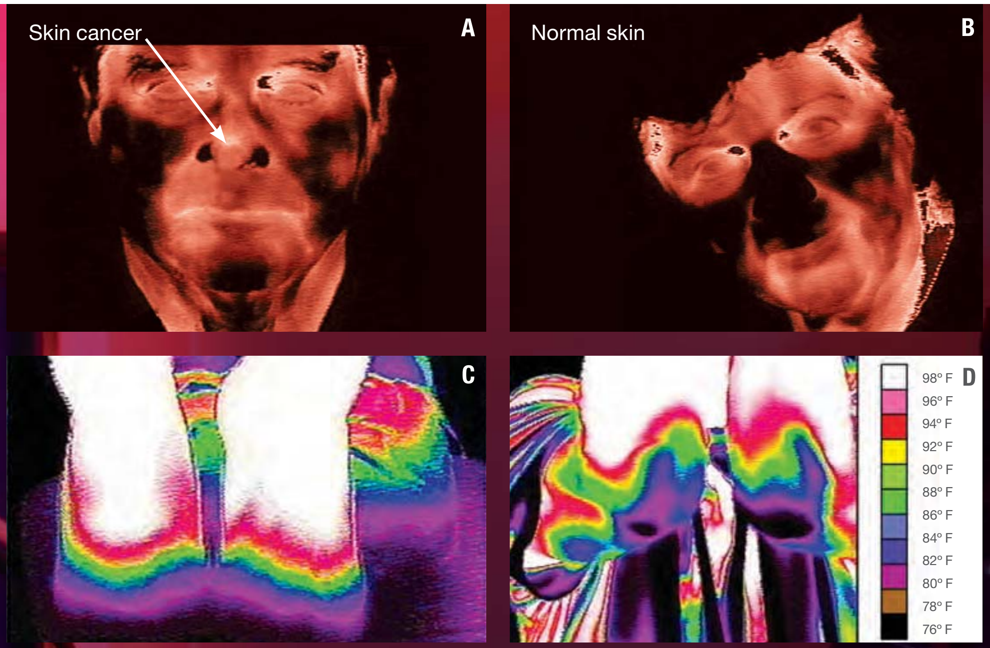


IMAGE A: This clearly shows the tip of the nose is warmer than its surrounding tissues due to the enhanced metabolic activity (angiogenesis) of a skin cancer. **IMAGE B:** A face with no skin cancer on the nose. Usually, nose and ears are colder relative to the other parts of the face, because those are extending out of the body. **IMAGE C–D:** This figure shows the temperature variation of the toes and elbows of a leprosy patient.

High Operating Temperature (HOT BIRD TECHNOLOGY)

IN THE LAST FEW YEARS, JPL has developed novel high operating temperature (HOT) barrier IR detector (BIRD) technology. HOT BIRD is a breakthrough technology, providing a leading edge for IR instrumentation by lowering the weight, size, and volume, while increasing the reliability due to a reduced cooling requirement. This will have a huge advantage for space-based IR instruments, because HOT BIRD arrays can be passively cooled in space. The NASA Office of the Chief Technologist, when briefed on HOT BIRD technology, provided funding at JPL via a Game Changing Technology Program to infuse this technology into NASA instruments. ■

Background image: Cory Hill prepares to remove the substrate of a BIRD FPA using the diamond point turning process.

Infrared image of a helicopter taken with a BIRD camera.

1-megapixel HOT-BIRD camera.

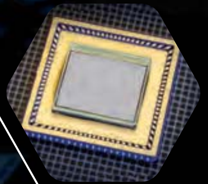
QUANTUM WELL INFRARED Photodetectors (QWIPs)

JPL IS RECOGNIZED as one of the world's leading institutions in infrared detector technology development. MDL performs cutting-edge research and development in innovative infrared (IR) detectors, focal plane arrays, and IR cameras for space and terrestrial applications. JPL's strength resides in its comprehensive end-to-end capabilities, encompassing device concept development, simulation and design of quantum structure devices, epitaxial growth of IR material and detector structures, material characterization, fabrication and characterization of infrared detectors and focal plane arrays, and incorporation of focal plane arrays into observational instruments. In the nineties, JPL pioneered the development of QWIP focal plane array technology for imaging applications and demonstrated the first LWIR hand-held camera based on QWIP technology, and also demonstrated the first megapixel, dual-band (4–5 μm MWIR and 7.5–9 μm LWIR) pixel co-located simultaneously readable QWIP FPA. JPL's work in the areas of QWIPs, quantum-dot infrared photodetectors (QDIPs), and antimonide-based superlattice barrier infrared detectors (BIRDs) is well documented in the scientific literature in over 300 publications and 22 patents. ■

PAST 25 YEARS
Pivotal Devices from MDL

'94

Demonstrated the first portable long-wavelength QWIP camera, opening up myriad applications in the civilian sector. Systems based on this technology have been deployed by FLIR Systems as the next-generation advanced infrared sensors for military applications.



'95

A revolutionary portable infrared video camera opened new vistas for doctors, pilots, environmental scientists, and law enforcement. This camera helped doctors detect tumors using heat signatures and helped pilots make better landings with improved night vision.

'00

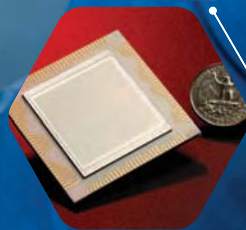
The four-band QWIP FPA can see up to 15.4 μm. This camera was flown over and imaged parts of Africa as a part of an international project to study the environmental impact of vegetation burning and related ecological effects.

'01

An early version of the breast cancer screening device "BioScan System" developed by OmniCorder Technologies, which licensed the JPL QWIP technology. This instrument received U.S. Food and Drug Administration clearance to market in January 2001.

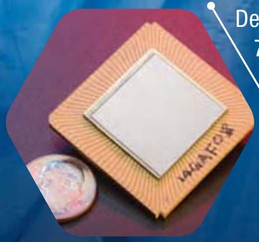
'02

A: Visible image of a brain tumor (most of the cancerous cells are dead due to cancer-sensitive drugs).
B: The thermal infrared image clearly discriminate the healthy tissues from dead tissues.



'06

First megapixel simultaneously readable and pixel co-registered dual-band QWIP focal plane array flown on Big Crow aircraft for a missile detection experiment.



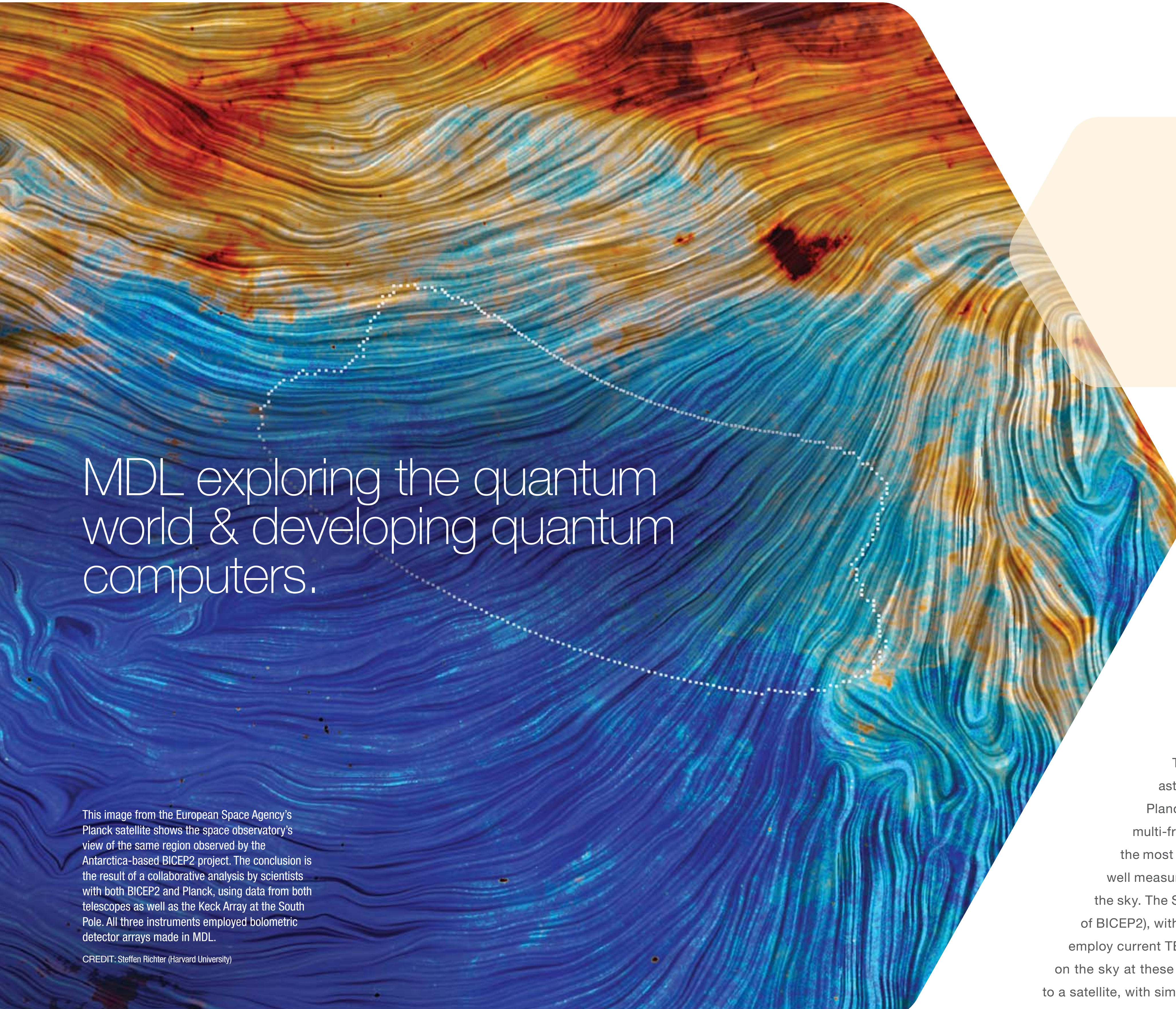
'10

Developed and delivered 7.5–12 μm dual-broadband QWIP focal plane array to Hyperspectral Thermal Emission Spectrometer (HyTES) airborne spectral imager, in operation since 2011.

'12

JPL's newest invention: a high operating temperature (HOT) mid-infrared VGA format BIRD camera. The focal plane array operates at 150 K with NEDT of 27 mK at 300 K background with f/2 aperture.

Background image: MDL's John Liu prepares for the focal plane array hybridization process.



MDL exploring the quantum world & developing quantum computers.

This image from the European Space Agency's Planck satellite shows the space observatory's view of the same region observed by the Antarctica-based BICEP2 project. The conclusion is the result of a collaborative analysis by scientists with both BICEP2 and Planck, using data from both telescopes as well as the Keck Array at the South Pole. All three instruments employed bolometric detector arrays made in MDL.

CREDIT: Steffen Richter (Harvard University)

"Balloon-borne observations represent an important milestone for advancing the readiness of **CMB detector technology.**"

WARREN HOLMES
Lead, *Superconducting Materials and Devices*

20 YEARS AT JPL

Superconducting MATERIALS & DEVICES

THE POSSIBLE DETECTION of an imprint by inflation on the polarization of the cosmic microwave background (CMB) excited both astrophysicists and the general public around the world in March 2014 when BICEP2 published its results. Inflation may produce a background of gravitational waves that produce a characteristic "swirly" CMB polarization signal called a B-mode pattern. The BICEP2 telescope, led by researchers at Caltech, Harvard, U. Minnesota, and Stanford, reported a B-mode pattern at 150 GHz. The extreme sensitivity needed to make this measurement was provided by JPL/MDL transition-edge sensor (TES) bolometer arrays, and an extensive three-year observation campaign from the South Pole. This led to a collaborative effort to determine the nature of the signal by many in the astrophysics community, including a collaboration between BICEP2 and the ESA/NASA Planck satellite, which observed the sky using earlier generations of MDL devices. Deep multi-frequency data are needed to separate the signal into CMB and Galactic components, the most significant Galactic signal arising from emission from interstellar dust, which is not well measured in polarization. In January 2015, the search for inflationary polarization took to the sky. The SPIDER balloon experiment launched carrying six focal plane arrays (each the size of BICEP2), with three observing at 150 GHz and three focal planes at 95 GHz. All six focal planes employ current TES bolometer arrays. The SPIDER balloon mission will increase the coverage area on the sky at these two frequencies. Balloon-borne observations represent the closest environment to a satellite, with similar scanning measurements and a hostile radiation environment, representing an important milestone for advancing the readiness of CMB detector technology. »

Concurrently, two different South Pole telescopes, Keck Array and BICEP3, are utilizing TES bolometer arrays. The Keck telescope array has been observing the same coverage of sky that BICEP2 observed, at both 150 GHz and 95 GHz, for the last three years. The Keck Array combines five BICEP2-style telescopes in a common barrel, making Keck a more sensitive multi-frequency system. The Keck Array will report on the signal observed by BICEP2 in the same region of sky in early 2015, and new results at 95 GHz later in the year. Two new focal plane units were installed during the short Antarctic summer to add measurements at a third frequency band at 220 GHz.

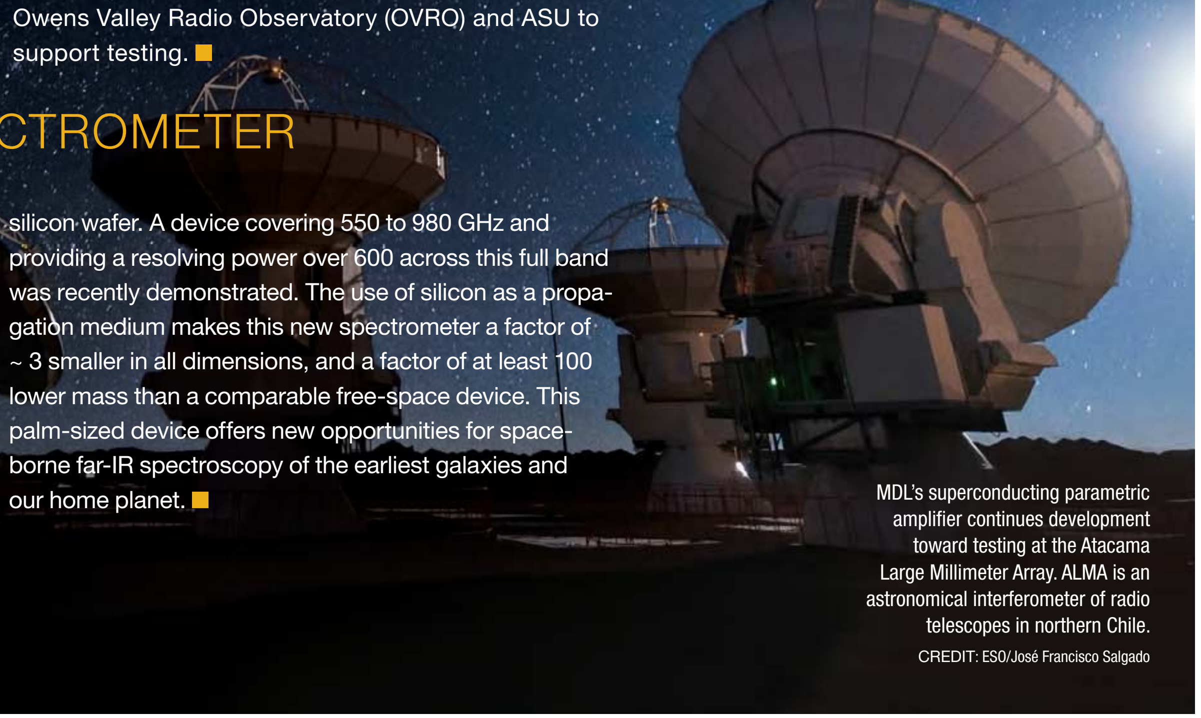
The BICEP3 telescope is also being fielded for its first season of observations in 2015. BICEP3 uses modular bolometer units developed at JPL to build a truly enormous focal plane collecting twice as much light as all five Keck Array telescopes combined. BICEP3 will use this technology to make sensitive observations at 95 GHz, expected to be the world's most sensitive instrument at this frequency when the system is fully operational. The same modular technology should be ideal for assembling and testing a large multi-frequency focal plane that will be needed in a future satellite mission to measure CMB polarization to fundamental limits. ■

TRAVELING-WAVE KINETIC INDUCTANCE
Parametric (TKIP) Amplifier

THE TRAVELING-WAVE kinetic inductance parametric (TKIP) amplifier is a new superconducting microwave amplifier technology first demonstrated at JPL in 2012 (Eom et al., *Nature Physics* 8(8), 2012). While previous superconducting microwave amplifiers have demonstrated quantum-limited sensitivity, their usefulness has been limited by very narrow bandwidth. The TKIP solves that problem by using a wide-band, traveling-wave design. Work has been ongoing, funded by a NASA APRA grant, to use the TKIP for improving low-temperature detector arrays for astronomy. The readout of a visible photon-sensing MKID array was recently accomplished, demonstrating improved SNR over a HEMT readout. A new project funded by the Laboratory for Physical Sciences (LPS) was started last year with the goal of using the TKIP to read out arrays of qubits. A quantum computer based on superconducting technology would require an amplifier that is both quantum limited and wide band, so the TKIP is an enabling technology for that new computing paradigm. A higher-frequency version of the TKIP, operating in the millimeter and submillimeter bands, would be of great interest for heterodyne receiver systems. Using funds from a spontaneous RTD grant, a W-band TKIP amplifier was designed and fabricated. Funding is currently being sought in collaboration with Caltech–Owens Valley Radio Observatory (OVRO) and ASU to support testing. ■

IMMERSION GRATING SPECTROMETER
with Quantum Capacitance Detector Readout

DEVELOPMENT CONTINUES on the quantum capacitance detector with the objective of developing a wafer-level spectrometer with moderate (R=600) spectral resolution and photon shot-noise-limited performance. The quantum capacitance detector is now mature, consistently yielding 10^{-20} W/Hz$^{1/2}$ noise equivalent power (NEP) with end-to-end efficiency of the order of 60%. The QCDs will be integrated onto a THz/far-IR waveguide grating spectrometer micromachined from a single 4-inch silicon wafer. A device covering 550 to 980 GHz and providing a resolving power over 600 across this full band was recently demonstrated. The use of silicon as a propagation medium makes this new spectrometer a factor of ~ 3 smaller in all dimensions, and a factor of at least 100 lower mass than a comparable free-space device. This palm-sized device offers new opportunities for space-borne far-IR spectroscopy of the earliest galaxies and our home planet. ■



MDL's superconducting parametric amplifier continues development toward testing at the Atacama Large Millimeter Array. ALMA is an astronomical interferometer of radio telescopes in northern Chile.
CREDIT: ESO/José Francisco Salgado

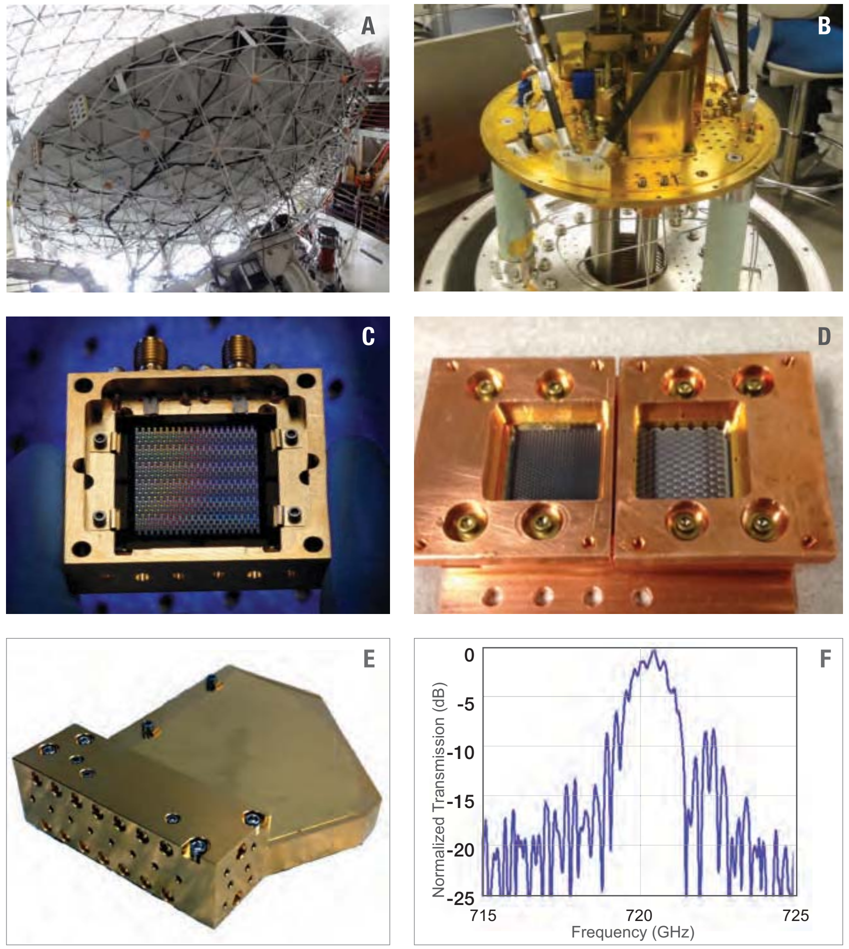


IMAGE A: MAKO on sky, May 2014, at the Caltech Submillimeter Observatory (CSO). Simultaneous readout was demonstrated with two arrays imaging at 350 μm and 850 μm. The low-frequency (< 250 MHz) FPGA readout demonstrated robust performance and successful integration with the telescope. **IMAGE B**: The MAKO cryostat utilizes both ^{4}He and ^{3}He systems to obtain base temperatures of 250 mK at the detector stage. **IMAGE C**: A 350-μm MAKO device fabricated using a novel interdigitated electrode coupling scheme developed at Caltech/JPL. The detectors and readout circuitry consist of a superconducting inductor and capacitor and are defined in only a single lithography step. **IMAGE D**: Fully packaged MAKO detector array. Detectors are back illuminated through silicon microlenses that appear as bumps in this picture. Left is the 350-μm array with pixel area of 1 mm^2, while on the right is the 850-μm array with pixel area 4 mm^2. **IMAGE E**: Silicon spectrometer wafer prototype assembled onto fixture for testing using a submillimeter vector network analyzer. The next milestone will be to use QCDs to read out the spectral channels. **IMAGE F**: Transmission between input feed and 720 GHz output port showing a spectral resolution R~600.

MULTIPLE Applications for MKIDs

2014 saw advancements in three projects largely funded through NASA grants. The far-infrared submillimeter-wave photometer (MAKO) returned to the Caltech Submillimeter Observatory (CSO) in August 2014, demonstrating nearly background-limited performance with a 488-pixel, 350-μm array and simultaneous readout on a single coaxial line with a first-generation 120-pixel, 850-μm array. The single-layer lithography and low-cost FPGA readout developed at JPL will make large-scale arrays possible in the far-infrared. Advancement in high-sensitivity devices for space astrophysics missions has focused on reducing absorber volume to increase detector responsivity. Pushing stepper lithography down to 150-nm-wide aluminum lines will allow mass production of arrays with significantly higher sensitivity. The superconducting microstrip spectrometer, Superspec, has had in-lab demonstrations of efficient channelization and NEPs approaching photon noise. This year, MDL reduced the inductor line width by a factor of two, decreasing the inductor volume and increasing the responsivity. ■

SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTORS

for Optical Communication and Quantum Optics

TUNGSTEN SILICIDE SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTORS (WSi SNSPDs) are a revolutionary technology for efficient time-resolved single photon counting in the infrared. In collaboration with NIST, JPL has been pioneering the advancement of WSi SNSPDs since 2011. These devices have recently demonstrated > 90% detection efficiency at 1550 nm, with 100 ps time resolution, 10 Mcps maximum count rates, and sub-Hz intrinsic dark counts. In 2013, 12-pixel arrays of WSi SNSPDs were successfully used to downlink optical communication data from the Moon at 79 Mbps in the Lunar Laser Communication Demonstration.

In 2014, 64-pixel arrays of free-space coupled WSi SNSPDs were demonstrated with a record-breaking 160x160-µm active area, along with advanced cryogenic readout electronics. Even larger arrays are currently in development for a future Deep Space Optical Communication (DSOC) technology demonstration project, where a future ground receiver at the Palomar Observatory will receive faint optical communication signals from Mars or beyond. In addition, WSi SNSPD arrays are under development for ultra-high-rate quantum communication, and JPL SNSPDs have been infused into a variety of quantum optics experiments at Caltech, MIT, Northwestern University, and others.

To increase the operating temperature of SNSPDs, nanowires were fabricated using the high-critical-temperature superconductor MgB_2. The 100-nm-wide, 20-nm-thick MgB_2 nanowires had a critical temperature of 33 K and responded to three photons with an ultra-fast (subnanosecond) current pulse. These results hold promise for high-temperature, ultra-fast, single-photon detectors. ■

NASA snaps infrared images of Saturn and its rings using the Cassini spacecraft.

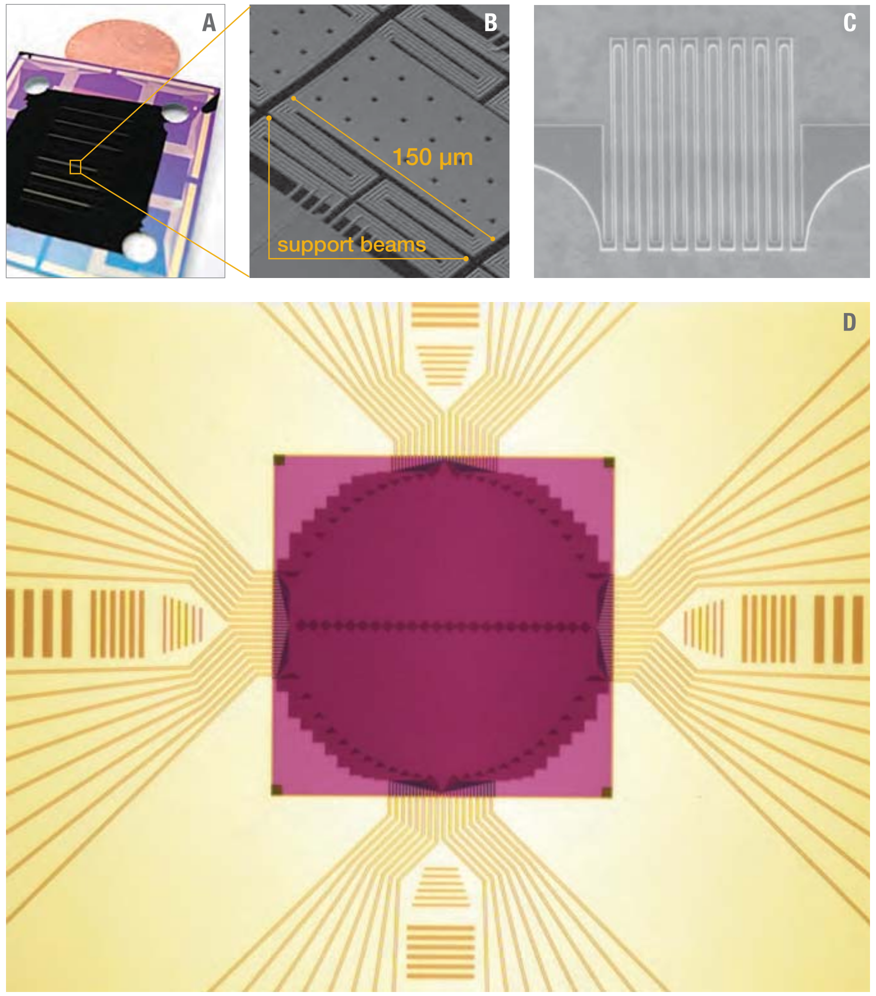


IMAGE A: Image of 64x16-element thermopile array for Diviner-Europa, a proposed instrument for NASA's Europa Mission. **IMAGE B:** Close-up micrograph of a single thermopile pixel. The performance of this pixel meets the requirements of Diviner-Europa. **IMAGE C:** Scanning electron microscope image of an SNSPD based on MgB_2. The nanowires are 200 nm wide and the active area is 10 x 10 µm². **IMAGE D:** Optical microscope image of a free-space-coupled 64-pixel SNSPD array for the DSOC ground receiver. The nanowires are 160 nm wide and the active area is 320 µm in diameter.

THERMOPILE Array

MDL HAS BEEN BUILDING THERMOPILE ARRAYS for a variety of spaceborne missions for well over a decade. Thermopiles are ideally suited for space because they require no cryocooler or bias circuit, are broadband, and are insensitive to temperature drift. A 64x16-element thermopile array was developed for Diviner-Europa (Diviner-E), which is a multispectral infrared imaging radiometer designed to fly on NASA's planned Flagship Europa mission. This array is ~ 10x larger than the current state-of-the-art arrays flying on JPL's Mars Climate Sounder (MCS) and Diviner. The performance of the array meets the requirements of Diviner-E. Additionally, custom readout integrated circuits (ROICs) were tested by JPL for performance and radiation tolerance. The custom ROIC meets the challenging total ionizing dose (TID) and single-event upset (SEU) requirements of the Europa mission. ■

SUPERCONDUCTING DEVICES & MATERIALS

Enabling Groundbreaking Science for 25 years

Pioneering **superconductor-insulator-superconductor (SIS) mixers** for frequencies spanning the range from 200 to 900 GHz are developed at MDL and fielded in ground-based and airborne telescopes.

Using a small focal plane of **spider-web bolometers**, the balloon-borne Boomerang telescope showed for the first time that the universe is "flat" based on unprecedented measurements of the cosmic microwave background.

Scientists at JPL and the Caltech campus invented and demonstrated the **microwave kinetic inductance detector (MKID)**, widely adopted worldwide for ground-based millimeter/submillimeter astronomy and also used for energy-resolved photon detection at optical, UV, and x-ray wavelengths.

First **superconducting polarimeters** developed based on in-phase-combined planar antenna arrays.

'93 '97 '99 '00 '01 '04 '05

SIS mixers and **spider-web bolometer arrays**, developed at MDL, are adopted as the baseline detectors in instruments HIFI, SPIRE, and HFI for the ESA missions Herschel and Planck.

High-sensitivity **uncooled thermopile arrays invented** and tested at MDL.

Polarization-sensitive bolometer invented at MDL. This detector was immediately adopted for the Planck flight mission.

First **superconducting nanowire single-photon detector (SNSPD)** made outside of Russia is fabricated and tested at the MDL.

MDL thermopile arrays used to make the first complete temperature maps of the Moon, including the coldest measured surface temperatures in the solar system.

The **microwave superconducting parametric amplifier invented at MDL** demonstrates near-quantum-limited sensitivity at 10 GHz. Device physics model predicts quantum-limited detection possible up to 800 GHz, nearly a factor 5 better than state-of-the-art semiconducting amplifiers.

Optical MKID array instrument fielded at Palomar makes state-of-the-art, submillisecond, time-resolved measurements of the Crab Nebula. Results highlighted in science technical news journals.

Planck releases highest precision ever temperature map of the cosmic microwave background based on measurements made with MDL spider-web bolometers.

The **quantum capacitance detector** is invented and demonstrated in MDL and achieves a world record for lowest noise IR detector.

Planck releases polarization map of cosmic microwave background made using **MDL polarization-sensitive bolometers**. Joint analysis with BICEP2 does not yet yield statistically significant detection of primordial gravitational waves.

MDL thermopile arrays have been used to measure the longest unbroken global temperature, dust, and water ice climatology for the atmosphere of Mars (> 8 years).

'09 '10 '11 '12 '13 '14 '15

Herschel–Planck launch with MDL-made **SIS mixers, spider-web bolometer arrays**, and **polarization-sensitive bolometers on board**.

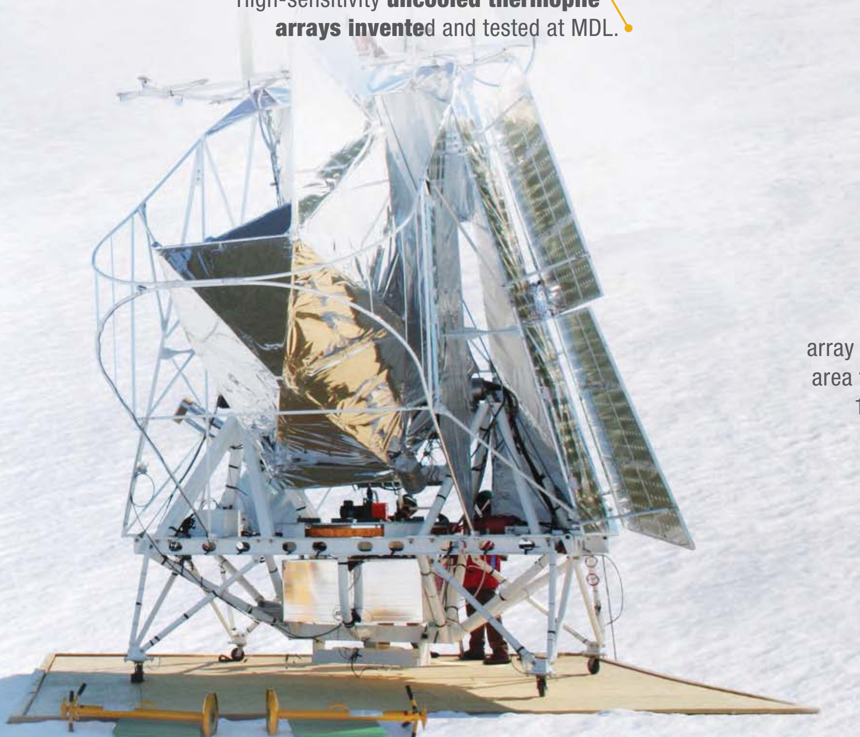
MDL-produced **SIS mixers on Herschel HIFI** discover many new terahertz spectral lines from molecules in interstellar space.

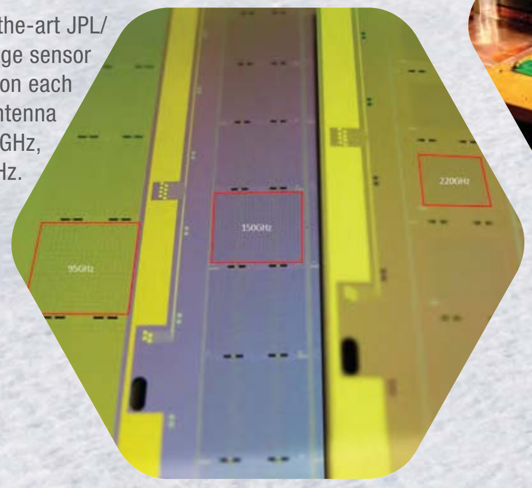
Spider-web bolometer detector arrays made for Herschel SPIRE instrument measure unprecedented large-area maps detecting distant infrared-luminous galaxies and closer to home detect argonium — ArH+, the first interstellar molecule containing a noble gas element.

SNSPD array made in MDL used in a ground station at Table Mountain, Calif., establishes an optical communication link with the LADEE satellite orbiting the Moon.

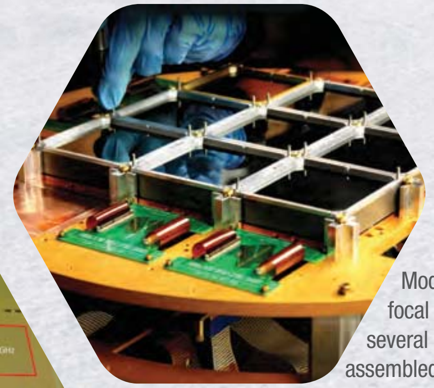
First light obtained with the **MAKO array** at CSO, which has a **484-element MKID array** made at MDL at the heart of the instrument.

Using **superconducting polarimeter arrays** fabricated at MDL, the BICEP2 experiment releases the most sensitive millimeter-wave polarization map made to date, in a search for "B-modes" indicative of primordial gravitational waves. Result is reported by international news agencies and science journals.

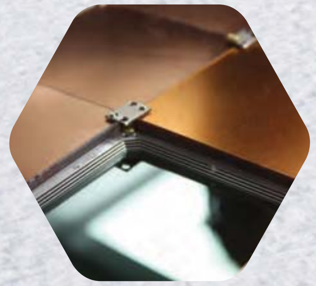




Current state-of-the-art JPL/MDL transition-edge sensor arrays. The outline on each array shows the size of antenna area for each pixel at 95 GHz, 150 GHz, and 220 GHz.



Modular 95-GHz focal plane with several modular units assembled in place.



SPIDER balloon experiment just before launch (image courtesy of the SPIDER collaboration).

Submillimeter-wave technology: A probe for space exploration.

False-color image showing the smooth Hapi region connecting the head and body of comet 67P/Churyumov-Gerasimenko. Differences in reflectivity have been enhanced in this image to emphasize the blueish color of the Hapi region. By studying the reflectivity, clues to the local composition of the comet are revealed. Here, the blue coloring might point to the presence of frozen water ice at or just below the dusty surface. The data used to create this image were acquired on August 21, 2014, when Rosetta was 70 km from the comet.

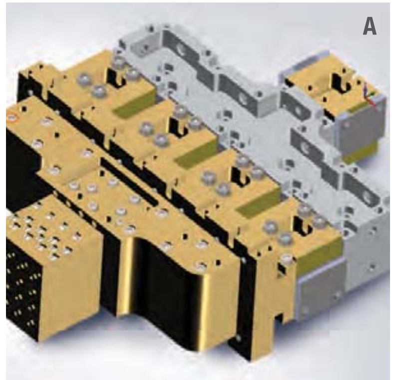
CREDIT: ESA/Rosetta/MPS for OSIRIS Team

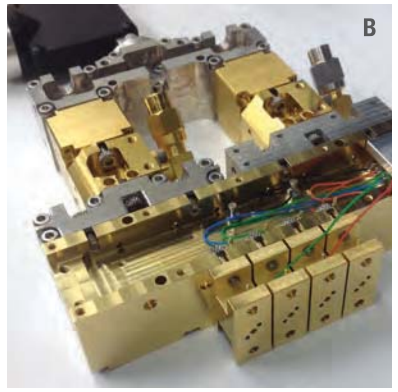
“Submillimeter-wave or THz technology reveals the physical and chemical processes involved in the **life-cycle of planets, comets,** and **even stars.**”

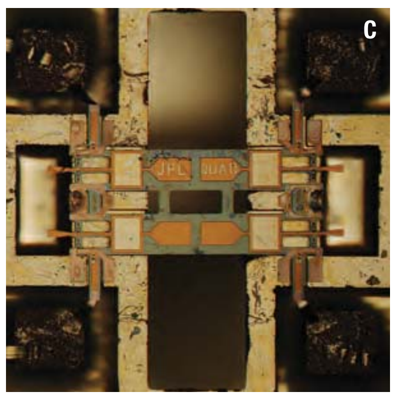
IMRAN MEHDI
Supervisor,
Instrument Electronics and Sensors
25 YEARS AT JPL

SUBMILLIMETER
Wave Advanced Technologies

RESEARCHERS in submillimeter-wave advanced technology at JPL specialize in developing and implementing submillimeter-wave and terahertz remote-sensing technologies for a variety of applications. The primary focus is to develop components and technologies to enable spaceborne instruments based on high-resolution heterodyne spectrometers for Earth remote-sensing missions, planetary missions, and astrophysics observatories. JPL's rich and varied technical expertise is also utilized for ground-based applications that are a spin-off from the heterodyne receiver technologies. Heterodyne technology allows one to map/detect unique molecular signatures with very high spectral resolution over a wide range of wavelengths. JPL/NASA has been the traditional leader in this field due to its wide applicability for astrophysics as well as Earth remote sensing. Next-generation technology development will allow us to build and deploy compact submillimeter-wave receivers that are ideally suited for planetary missions. »







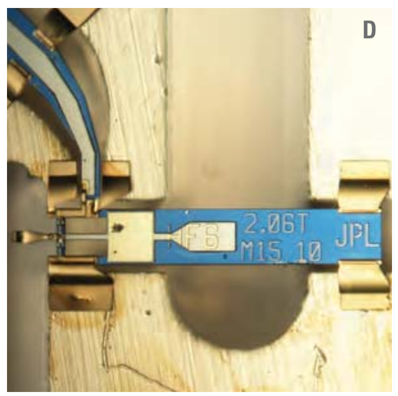
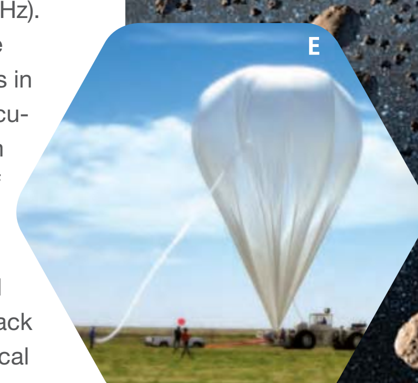


IMAGE A: A 16-pixel, 1.9-THz local oscillator (LO) source prototype for next-generation terahertz cameras. **IMAGE B**: 1.47-THz 4-pixel LO subsystems for STO-2. **IMAGE C**: A 520–600-GHz on-chip power combined frequency tripler. **IMAGE D**: A bias-able 1.9–2.06 THz frequency tripler for radio astronomy. **IMAGE E**: A high-altitude balloon will be launched from Antarctica next year to study star formation. It will carry detectors and local oscillators made in the MDL.

A HIGH-ALTITUDE BALLOON

Instrument for Studying the Life-Cycles of Stars

THE STRATOSPHERIC TERAHERTZ OBSERVATORY (STO-2) is a NASA-funded long-duration balloon (LDB) experiment designed to address a key problem in modern astrophysics: understanding the life-cycles of star-forming molecular clouds in the Milky Way Galaxy. To accomplish this goal, STO will survey a section of the Galactic plane in the luminous interstellar cooling line at 158 μm (1.90 THz) and the important star-formation and ionized-gas tracer at 205 μm (1.45 THz). The 4-pixel heterodyne receiver arrays on board STO possess the sensitivity and spectral resolution needed to see molecular clouds in the process of formation, measure the rate of evaporation of molecular clouds, and separate the bulk motion of gas in the Galaxy from local kinematic effects. By building a three-dimensional picture of the interstellar medium of the Galaxy, STO will be able to study the creation and disruption of star-forming clouds in the Galaxy, determine the parameters that govern the star-formation rate, and provide a template for star formation and stellar/interstellar feedback in other galaxies. JPL's MDL is at the forefront of producing the local oscillator and hot-electron mixers for this important mission. ■



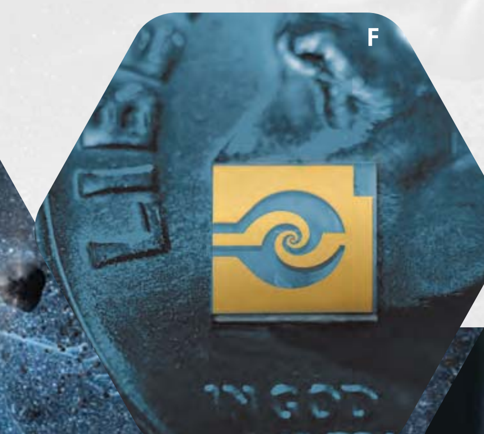
NEOWISE, the asteroid-hunting portion of NASA's Wide-field Infrared Survey Explorer, was able to crack the centaur mystery thanks to its ability to see the infrared properties of the small objects. The infrared data, together with previous visible-light observations, showed that many of the centaurs are dark like soot and blue-gray in color, telltale signs of comets.

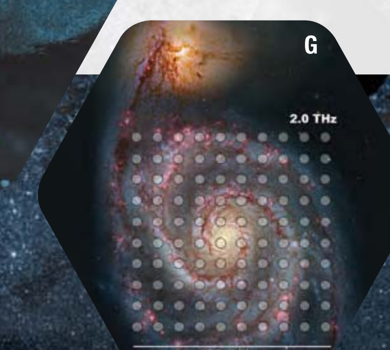
NOVEL HOT-ELECTRON BOLOMETER

(HEB) Detector Utilizing MgB_2 Superconductor

EXTREMELY HIGH SENSITIVITY detectors are required for investigating the star-forming regions of the universe and making quantitative measurements on abundances of various molecular species in areas of active star formation. A novel terahertz (THz) radiation mixer made from the high-critical-temperature superconducting material MgB_2 has recently been demonstrated. Even though superconductivity in MgB_2 with critical temperature ~ 40 K was discovered in 2001, only now have ultrathin high-quality films become available. Such films are the key in achievement of the high thermal relaxation speed (wide mixer bandwidth). JPL has developed quasi-optical MgB_2 HEB mixers for the 0.6–2.5 THz range and performed a series of proof-of-concept tests demonstrating the large mixer bandwidth (up to 8.7 GHz) and low noise temperature (≈ 1,000 K, double-sideband). Another important benefit of the new technology is the possibility of operating the mixer at 20–25 K. This will allow for a much simpler and less expensive cryocooling approach, especially on spaceborne platforms. For comparison, the Herschel HIFI instrument required liquid helium for cooling, which eventually limited the mission lifetime to ~ 3 years. ■

IMAGE F: A new generation of hot-electron bolometric chips based on MgB_2 is being developed at JPL. This chip is fabricated with a spiral antenna, placed on top of a U.S. quarter shown for size. These chips will provide extreme sensitivity, operating only at 20–25 K. **IMAGE G:** Work is underway to develop a 100-pixel array receiver that can enable increased science throughput from features such as the Horsehead Nebula (Barnard 33 in the constellation Orion).





MDL-PRODUCED DEVICES

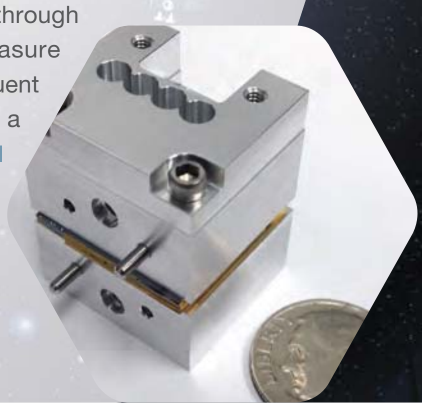
Instruments for Planetary Exploration

DETECTION OF WATER molecules in the universe is a long-standing goal of NASA planetary missions. Currently, MDL-produced devices are on board the MIRO (Microwave Instrument for the Rosetta Orbiter). MIRO first detected water vapor from the coma of comet 67P/Churyumov-Gerasimenko in June 2014, when Rosetta was 350,000 km from the comet nucleus. At that distance, the nucleus was unresolved and the entire coma filled MIRO's field of view. Now that Rosetta has rendezvoused with the comet, MIRO has begun observations to map the nucleus and coma in great detail. More recently, the MIRO instrument has detected an increase in the rate of water vapor coming from the comet, confirming that the water vapor rate on the comet is not constant. MIRO is producing scientific results that will improve our understanding of chemical and physical processes on planetary bodies. Advanced devices are being designed and fabricated at the MDL that will allow lower-mass and lower-power heterodyne receivers with greater sensitivities to hunt for water in the universe. A proposed instrument to Europa, part of the Europa Clipper mission under consideration by NASA for a 2025 launch date, will allow scientists to investigate plumes on Europa. ■

COMPACT SUBMILLIMETER-WAVE

Instruments for Planetary Exploration

NASA HAS FUNDED development of a super-compact submillimeter-wave instrument for planetary exploration. Using newly developed silicon micro-machining technology that enables a low-mass and highly integrated receiver, the Planetary Instrument for Submillimeter-wave Surface and Atmospheric Reconnaissance and Research in Orbit (PISSARRO) will provide a state-of-the-art submillimeter-wave radiometer/spectrometer for orbiter missions to Mars, Venus, Titan, and the Galilean moons. PISSARRO will allow a large number of chemical species, such as water, NO_2, N_2O, NH_3, SO_2, H_2S, CH_4, and HCN, among others, to be detected at concentrations below a part per billion. In exploring planets and their moons from orbit, PISSARRO will gather data on the thermal structure, dynamics, and composition of planetary atmospheres and surfaces. In radiometer mode, the instrument will measure the polarized thermal emission, revealing aspects of a body's chemical composition and physical state. As a spectrometer, PISSARRO will investigate the sources and sinks of trace gases and globally characterize the atmosphere with high spectral, spatial, and temporal resolution uniquely available through submillimeter-wave spectroscopy. It will also measure wind speeds, temperature, pressure, and key constituent concentrations in the planetary atmospheres with a higher precision than any other available technology. ■



NASA's contribution included three of the orbiter's instruments (the Microwave Instrument for Rosetta Orbiter, the Ion and Electron Sensor, and an ultraviolet spectrometer called Alice). The Microwave Instrument for the Rosetta Orbiter was built at JPL and JPL is home to its principal investigator, Samuel Gulkis.

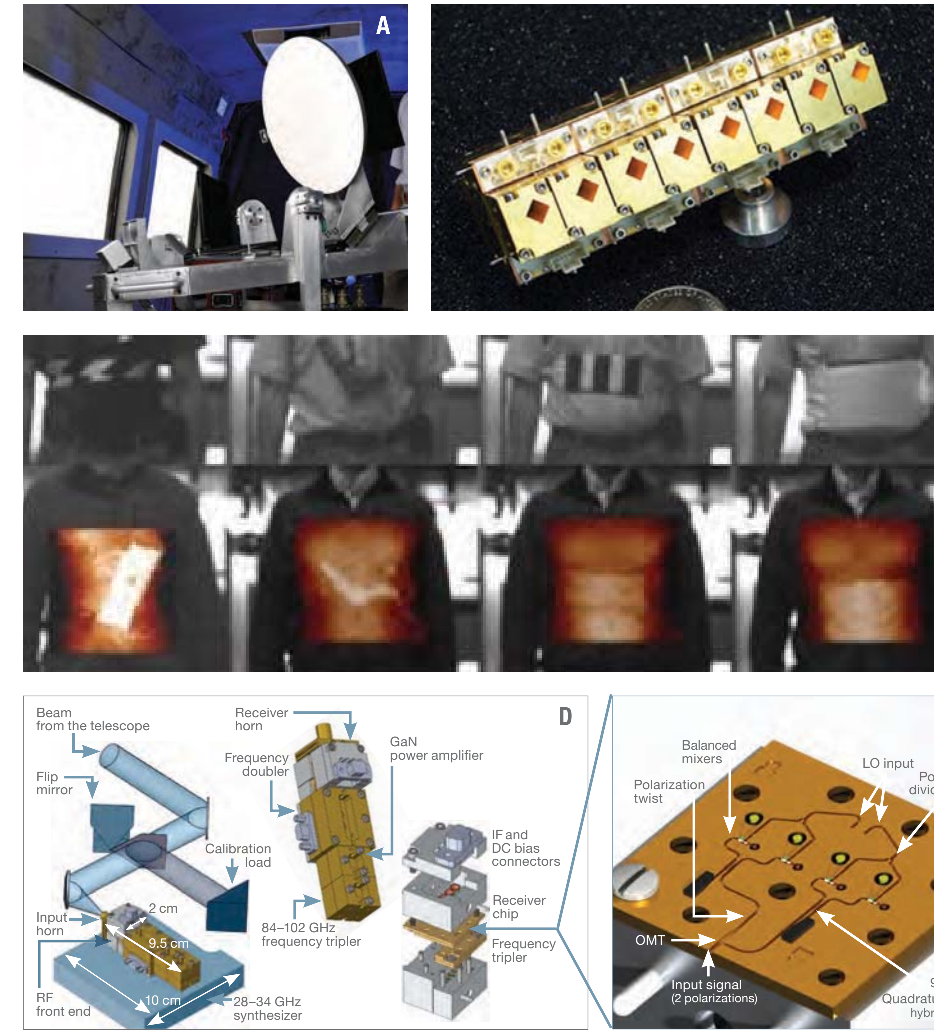


IMAGE A: A portable imaging radar system has been developed that utilizes state-of-the-art receivers for providing high-resolution images. **IMAGE B:** An 8-pixel transreceiver array has been developed at 340 GHz for the radar platform. **IMAGE C:** This panorama shows a series of four images. The top ones are optical while the bottom panels show THz images obtained with the platform in IMAGE A. Artifacts hidden under a winter jacket are visible in the THz images. **IMAGE D:** Compact instruments are being designed based on MDL proven technology that can shrink the size and volume of future planetary instruments. **IMAGE E:** Close-up of the silicon piece from IMAGE D is shown; this very light silicon structure includes submillimeter-wave components such as an OMT, mixer, and multiplier.

MDL LEVERAGES SPACE TECHNOLOGY

for a Safer Planet Earth

SUBMILLIMETER-WAVE components and receivers that have been developed for space applications can also be used for applications on planet Earth. A portable radar system was demonstrated in 2014 that can provide imaging of targets by revealing artifacts behind clothes (thus undetectable with regular cameras). The technology developed at JPL, based on devices from MDL, can work at 340 GHz and 670 GHz, the highest reported frequency for such an application. In 2014, an 8-pixel radar camera was implemented that allows for real-time imaging of targets. This is a breakthrough and allows one to image a wide scene with centimeter-scale resolution. This system is portable and can be mounted in a vehicle, as was done by MDL scientists to study dust storms in the Mojave Desert. This instrument has scientific applications for studying the dynamics of dust storms or volcanic eruptions on Earth as well as other planets. ■

SUBMILLIMETER-WAVE TECHNOLOGY

A Hunt for Water, Heat, and Molecules in the Solar System and Beyond

Development of the world's first 2.5-THz mixer based on Nb HEB. Similar devices were later used on Herschel's HIFI instrument.

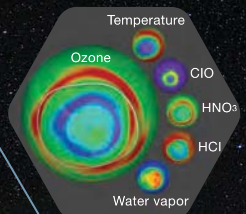


Figure from EOS MLS instrument showing the capability of the submillimeter-wave instrument.

'90

Development and delivery of diode receivers for Earth observations on the UARS MLS spacecraft. Monitoring of ozone chemistry.

'91

Onwards: Development of first planar Schottky diode mixer and multipliers.

NASA's Upper Atmosphere Research Satellite (UARS) with JPL's Microwave Limb Sounder (MLS) as one of its 10 instruments was launched September 12, 1991. The major objective of UARS MLS was, in response to the industrial chlorofluorocarbon threat to the ozone layer, to provide global information on chlorine monoxide (ClO), the dominant form of chlorine that destroys ozone.

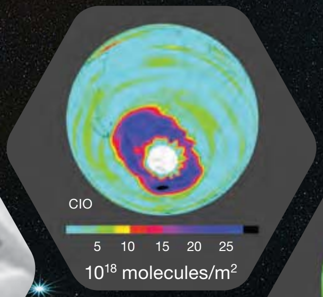
'01

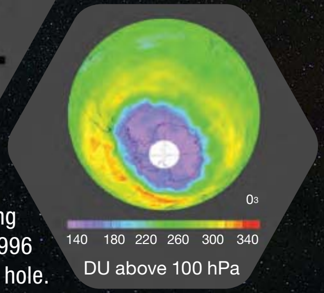
Delivery of 557-GHz Schottky diode receiver for the MIRO instrument on ESA's Rosetta spacecraft. MIRO made contact with Lutetia (in 2000) and is currently taking science data on comet CG.

'04

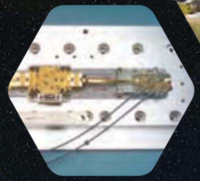
The Earth Observing System (EOS) Microwave Limb Sounder (MLS) is one of four instruments on NASA's EOS Aura satellite, launched on July 15, 2004.

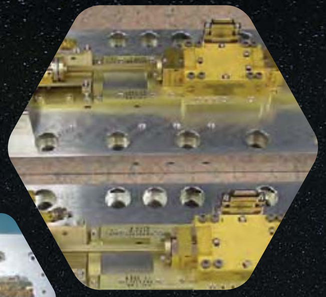
Rosetta is a spacecraft on a 10-year mission to catch a comet and land a probe on it. Launched in 2004, the spacecraft arrived at its target, comet 67P/Churyumov-Gerasimenko, on August 6, 2014.

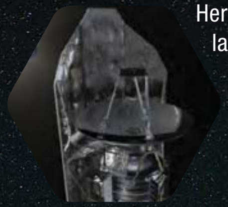




The images show MLS O_3 and ClO measurements made during development of the 1996 Antarctic ozone hole.



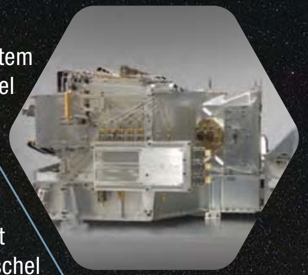




Herschel Space Observatory, launched May 14, 2009, carries local oscillator and mixer devices designed and fabricated at the MDL.

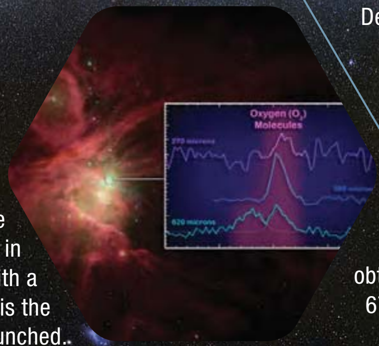
'05

Delivery of LO chains for the HIFI instrument on board ESA's Herschel Space Observatory.



HIFI LO subsystem used on the Herschel Space Observatory.

'09



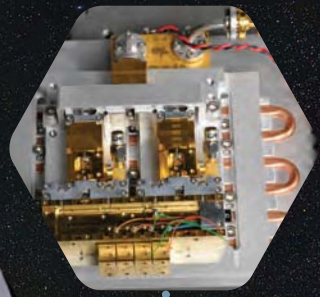
Herschel was launched on May 14, 2009. It is the fourth "cornerstone" mission in the ESA science program. With a 3.5-m Cassegrain telescope, it is the largest space telescope ever launched.

'11

670-GHz radar demonstration.

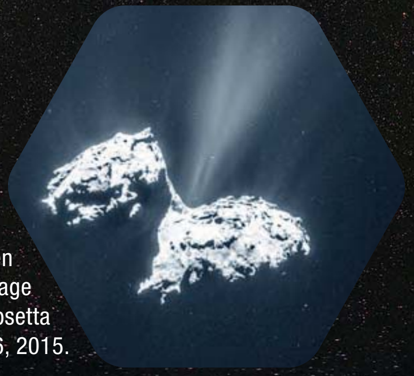
Demonstration of the first imaging radar at 670 GHz.

'14



A 4-pixel 1.47-THz LO source has been developed for the Stratospheric THz Observatory (STO-2).

The camera aboard Rosetta's lander, Philae, obtained this image of comet 67P/Churyumov-Gerasimenko on October 7, 2014.



The sheer size of comet 67P/C-G's jets can be seen in this wide-view image captured by Rosetta on February 6, 2015.

A 360-degree panoramic image, covering the entire southern and northern celestial sphere, reveals the cosmic landscape that surrounds our tiny blue planet. The plane of the Milky Way Galaxy, which we see edge-on from our perspective on Earth, cuts a luminous swath across the image.

CREDIT: ESO/S. Brunier

Hot fluids circulating through magnesium-rich basalt can produce methane.

Advanced microdevices for prolonged operation in harsh environments.

> “When developing a **new technology**, some of the seemingly simple obstacles that we take for granted turn out to be quite complicated to overcome.”

HARISH M. MANOHARA
Principal Staff/Group Supervisor, *Nano and Micro Systems*
15 YEARS AT JPL

NANO & MICRO **Systems**

THE PAST YEAR has been the “delivery” year for nano and micro systems. This is the most satisfying aspect of applied research, where a new technology is nurtured from its conception to a field-test-ready product, or in some cases, a laboratory-proven product ready for the next bigger stage. The year 2014 saw about five different technology-development efforts reach their planned culmination resulting in deliverables. MDL successfully delivered on a novel sample presence verification sensor concept for primitive-body sample-return missions; a functioning RF-powered sample-extraction system: the MicroExtractor, or µ-EX, for in situ planetary exploration instruments; a miniature vacuum triode that uses carbon nanotube field emitters and hybrid microassembly to drive an oscillator at high temperature for oil and gas industry application; micromachined, high-temperature-tolerant, robust capacitors for down-hole circuits for oil and gas industry application; and a functional laboratory prototype of a miniature stereo endoscope with panning capability for minimally invasive neurosurgery applications. Many of these products are now entering the maturation phase that is uniquely different for each with varying degrees of complexity and challenges. We are looking forward. »

Dr. Valerie Scott prepares to test a CNT mini X-ray tube in the characterization chamber.

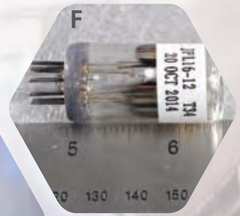
MINIATURE X-ray Imaging / Spectroscopic Tool

JPL'S CARBON NANOTUBE (CNT) field-emission technology has been used to realize a preliminary version of an imaging/spectroscopic tool suitable for harsh-environment applications. Such a tool is desired for in situ applications to acquire real-time penetrative images as well as elemental composition data of the surrounding geological features. The tool is also useful for oil and gas industry applications in open wells. The problem, however, is the unavailability of a compact X-ray source and imaging/spectroscopic system that can be integrated into an actuating tool (for example, a robotic arm). JPL is developing a compact version of such a tool with potential to tune the source energy. Using robust CNTs to produce field-emission electrons, a miniature X-ray tube using various target anodes, selected to cover the design energy range, was demonstrated along with its ability to produce transmission and backscatter spectra of a shale sample in a laboratory setting. ■

HIGH-TEMPERATURE CNT Vacuum Electronics

RECENT DEVELOPMENTS in high-temperature CNT vacuum electronics at JPL have been focused on readying active devices for actual field testing in high-temperature environments. Using a manual hybrid assembly and compact glass bulb vacuum packaging techniques, several vacuum electronic active devices using CNT field emitters have been fabricated for high-temperature applications. These active devices are assembled in layers using a hybrid microassembly process that is being automated. The electrode stack is mounted on a standard commercially available header, which is then inserted inside a miniature glass bulb for vacuum packaging. These active devices have been tested and deemed ready for field testing in elementary circuits. These active devices will be coupled with high-temperature micromachined capacitors also being developed at JPL. In this past year, challenges concerning robustness of CNTs, repeatability of the microassembly process, and reliability of the vacuum packaging process have been addressed. ■

F



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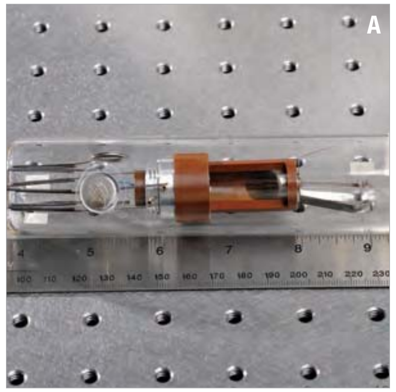

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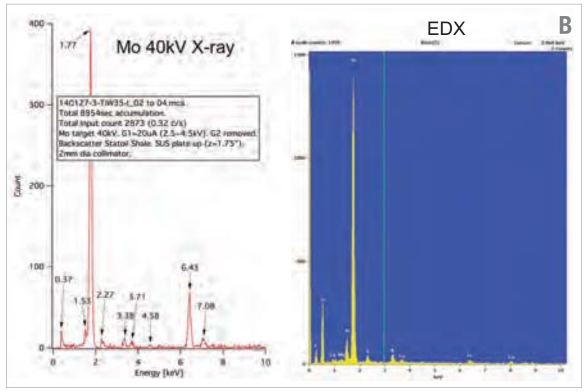

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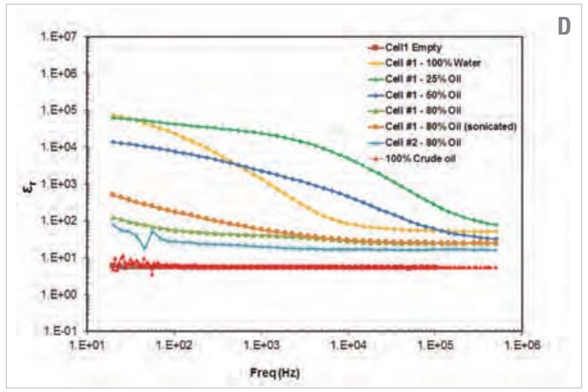
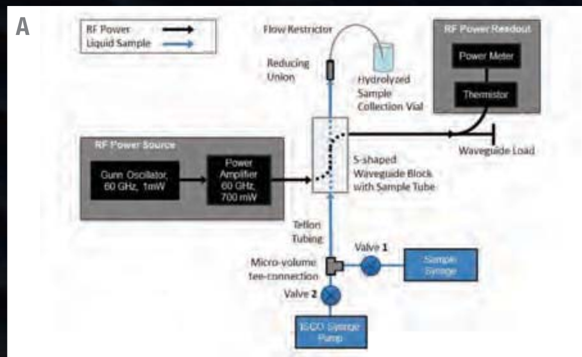


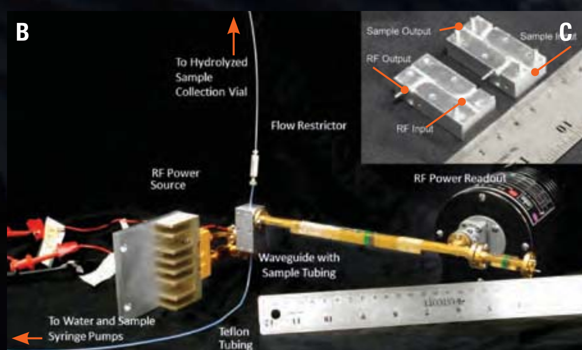
E

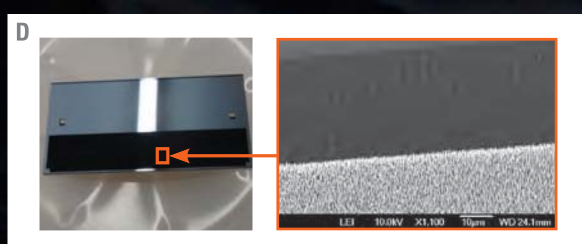
IMAGE A: Photograph of miniature X-ray tube using CNT field-emission source. **IMAGE B:** Comparison of backscatter spectra obtained using the miniature CNT X-ray tube of a shale sample versus the EDX spectrum of the same sample. Notice the similarity of elemental fluorescence map. **IMAGE C:** Photograph of a composition sensor based on dielectric spectroscopy technique showing two electrodes embedded inside a ceramic body. **IMAGE D:** Graph showing detection of mixture ratio between water and hydrocarbon at different excitation frequencies. **IMAGE E:** The Solar Probe Plus spacecraft, with solar panels folded into the shadows of its protective shield, gathers data on its approach to the Sun. **IMAGE F:** Miniature glass bulb vacuum-packaged CNT triode.

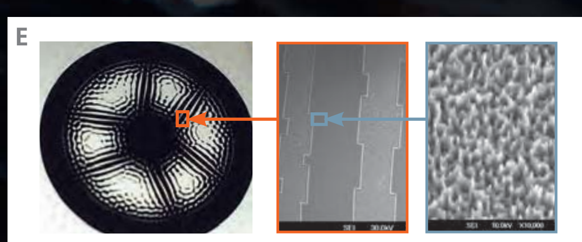
HARSH-ENVIRONMENT SENSORS for Space and Terrestrial Applications

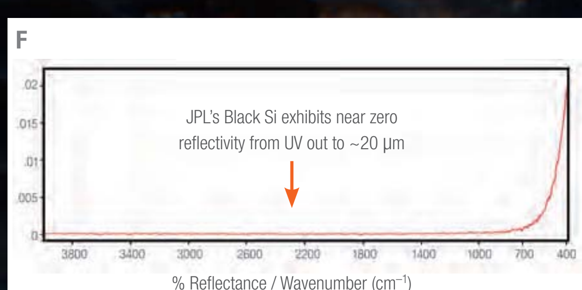
JPL CONTINUES to develop microsensors to monitor parameters such as temperature, pressure, fluid flow rate, and mixture composition in harsh environments. While an extended version of these sensors is useful for space applications, the immediate version is for use in the oil and gas production environment. Many challenges arising from high-temperature, high-pressure corrosive environments are being resolved methodically to realize a sensor system that can be integrated into an overall system. The system integration requirement has brought about new challenges in the areas of integration mechanics, packaging, electronics, and interconnects that are being addressed by JPL by merging both customized designs and adaptation of commercial-off-the-shelf (COTS) components. One example of unique adaptation is in composition sensing that is based on dielectric spectroscopy technique. JPL has tested and qualified this sensor in different mixture ratios of different fluids. This sensor can operate at temperatures above 200 degrees C. ■











RF-POWERED
Micro-extractor and Reactor (µEX)

JPL HAS DEVELOPED an RF-powered microreactor as part of potential in situ exploration missions to inner and outer planetary bodies for sample processing and extraction. This technology utilizes aqueous solutions subjected to 60-GHz radiation at 730 mW of input power to extract target organic compounds and molecular and inorganic ions as well as to hydrolyze complex polymeric materials. Successful identification and characterization of key target molecules rely on the sample-processing techniques utilized alongside state-of-the-art detection and analysis. µEX potentially offers a simplified alternative to the typical gold-standard extractions that often use solvents, chemicals, and conditions that can vary wildly and depend on the targeted molecules. Instead, this instrument uses a single solvent—water—that can be "tuned" under the different experimental conditions, leveraging the operating principles of the subcritical water extractor. Proof-of-concept experiments have been done examining hydrolysis reaction chemistry and extraction of several target molecules, such as amino acids. ■

JPL BLACK Silicon Technology

JPL HAS DEVELOPED a cryo-etch silicon surface texturing technique (i.e., "black silicon") that is rapid, repeatable, and robust with process parameters adjustable for optimization of texture characteristics depending on utilization. Multiple applications exist: the resultant area enhancement has applications in thermal management and in electrical devices such as capacitors and batteries; the texturing enables the surface to be made either super hydrophobic or super hydrophilic, with applications in microfluidics and ion propulsion; and the high light-trapping capability finds applications in fabrication of antireflective surfaces for optical instruments such as imaging spectrometers and coronagraphs. The ability to define ultra-black surfaces adjacent to highly reflective or transmissive surfaces with lithographic precision has enabled JPL's black silicon technology to be incorporated into several flight instruments, including HyTES, AVARIS, UCIS, HyspIRI, MaRS2, PRISM, and NEON. ■

IMAGE A: Schematic flow chart of the RF-powered micro-extraction process. **IMAGE B:** Photograph of the RF-powered micro-extractor. **IMAGE C:** S-shaped waveguide. **IMAGE D:** OCO_2 spectrometer slit. **IMAGE E:** WFIRST-AFTA high-contrast imaging apodizer for planet finding near bright parent star. **IMAGE F:** Cryo-etched black Si reflectance as a function of wavelength.

NANO & MICRO Systems Highlights

'02

Development of a MEMS gyroscope with the best reported bias stability for spacecraft and defense use.

'05

First high-current density CNT field-emission sources developed.

Nano and micro systems research started.

'07

New sample verification sensor system for lunar mission developed.

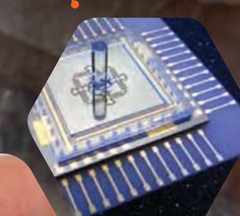
Si DRG IP leads to a spin-off.

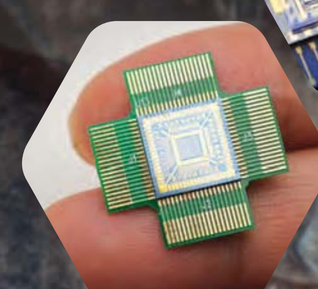
'11

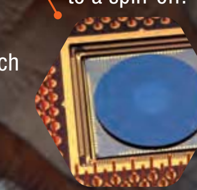
New miniature stereo imaging system for 3D imaging: 3D-MARVEL spin-off started.

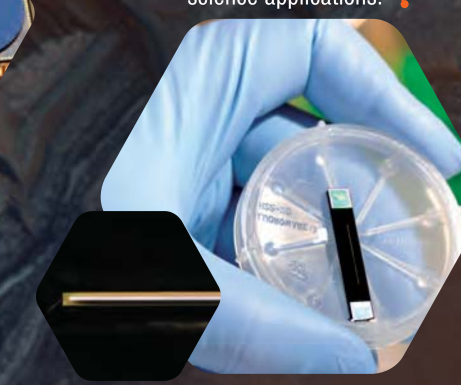
'13

Development of black Si technology to enhance the performance of imaging spectrometers for Earth science applications.









Background image: This is an enhanced-color view generated from images acquired by the High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter (MRO).

MEP thruster under a measurement microscope during alignment of 400 emitter needles and extractor apertures within 10 µm of center of the 40-µm-diameter apertures.

Electrospray propulsion systems... scalable and high precision.

“MEP will revolutionize small **spacecraft propulsion** capabilities.**”**

COLLEEN MARRESE-READING

Principal Investigator, *Microfluidic Electrospray Propulsion*

20 YEARS AT JPL

MICROFLUIDIC
Electrospray Propulsion (MEP)

ADVANCES in microfabrication capabilities are enabling the development of arrays of silicon electrospray needles for highly compact, integrated, scalable indium-fueled electrospray thrusters. The silicon emitter array chips have 400 needles in 1 cm^2 that are about 300 µm tall with tapered sidewalls and axial grooves for capillary-force-driven propellant flow. They are patterned using gray-scale electron-beam lithography to write a complex 3-D resist exposure profile and etch mask. The emitters are loaded with a thin film of indium propellant using microfabrication facilities. The heater to melt the indium is fabricated from pyrex and silicon chips and then bonded to the emitter array chip using anodic bonding. The thruster assembly also includes an extractor electrode, high-voltage isolator, propellant management device, and an assembly structure. Kilovolts are applied between the needles and the extractor with apertures aligned to the needles to deform the indium into a liquid cone at the apex of the needles and then extract and accelerate ions to tens of thousands of meters per second to create thrust. The feed system is highly integrated into the thruster head because it is based on capillary forces only with no valves or pressurized reservoir. This approach to electrospray propulsion will improve on the state of the art in volume and mass by more than 10 times. This technology has recently demonstrated operation at over 100 micronewtons of thrust and hours of stable operation at lower thrust levels. »

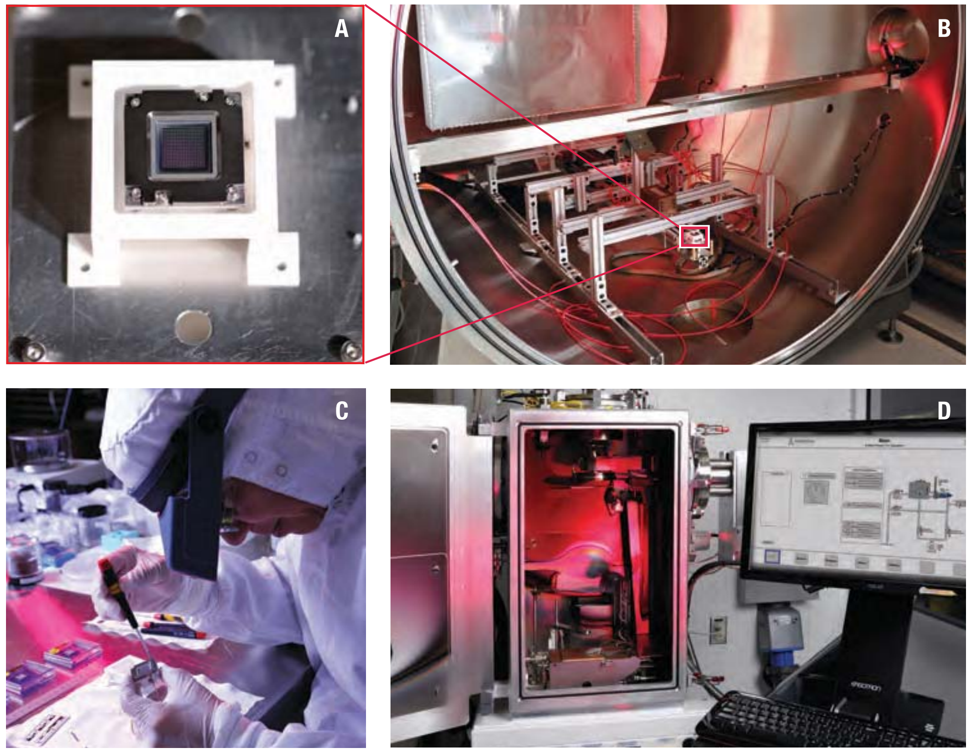


IMAGE A: 100-micronewton prototype MEP thruster in a thermal shield. **IMAGE B:** MEP thruster on a micronewton thrust stand in a 2-meter-diameter vacuum chamber for testing. **IMAGE C:** MEP thruster being assembled. **IMAGE D:** Chamber of the combined e-beam/thermal deposition system used to pre-load the emitters with propellant.

MEP Will Enable Nanosats with Extraordinary PROPULSION CAPABILITY

MEP TECHNOLOGY is highly compact, with microfabricated components, a capillary-force-driven feed system, and solid high-density indium metal propellant that are all integrated into the thruster head for a highly distributable propulsion architecture with a very high delta-v capability on very small spacecraft. This thruster technology would provide both primary propulsion and attitude control with eight thrusters to enable interplanetary CubeSats and CubeSats for Earth orbit with much greater orbit maneuvering capabilities than large spacecraft. It operates at a specific impulse of > 5000 s to enable 1000 m/s of delta-v capability on a 3U CubeSat with only 60 grams of indium in a volume less than 10 cm^3. CubeSat swarms with MEP could be released to characterize asteroids. CubeSats with MEP could return samples from Mars. They could be released from much larger spacecraft to assemble into complex architectures. ■

Microfabricated ELECTROSPRAY NEEDLES

JPL HAS DEVELOPED a microfabrication process for 3-D electrospray needle arrays, using a combination of gray-scale electron-beam lithography and deep reactive ion etching (DRIE). A high-resolution e-beam-sensitive photoresist is exposed in increments of nonlinear doses, and developed in an iterative manner to achieve accurate depth of the 3-D shapes. A custom DRIE process is then applied, to achieve tall needles (> 300 μm) with tapered sidewalls and integrated grooves. Finally, the arrays are metallized with propellant. This novel and unique process to fabricate complex 3-D structures not only enables microfabricated electrospray systems but is also beneficial for biomedical and surgical microneedle devices, lasers and photonics crystals, or microfluidics channels for precise spray-gun applications. ■

The bonded emitter array and heater is pre-loaded with indium propellant in a combined e-beam/thermal evaporation system. The chip is mounted on a rotating arm that has three axes of rotation to allow for conformal coating of complex 3D structures.

MEP Will Enable New Spacecraft CONTROL PARADIGMS

SEVERAL THRUSTERS can be distributed on very small or very large spacecraft to provide attitude control to much higher precision than reaction wheels while significantly reducing system mass, volume, and control complexity. Study results suggest that MEP could precision point exoplanet observatories to 40 times better precision than that of the Hubble Space Telescope, which is currently state of the art in pointing precision. They would enable eliminating reaction wheels, vibration isolation hexapods, and hydrazine thrusters to off-load them. They will have the capability to operate continuously for years using only hundreds of grams of indium propellant. The high-voltage power-processing units are under development to integrate with single or multiple thrusters on 10x10 cm, enabling distribution of complete propulsion system units with control of any of the integrated systems via several low-voltage wires only to the spacecraft avionics unit. ■

MICROFABRICATION OF COMPLEX 3D GEOMETRIES for Microfluidic Electrospray Propulsion Systems

Image of Saturn's icy moon Enceladus acquired by NASA's Cassini spacecraft. The blue "tiger stripes" in the lower portion of the image are geologically active "geyser" features, which spray icy, organic-laden material into space.

JPL is developing instruments to search for chemical evidence of life on Europa and Enceladus.

> "By analyzing distributions of organics on other worlds, we can search for patterns that we may recognize as life, very similar or very different from our own."

PETER WILLIS

Senior Technologist, *Microfluidic Life Analyzer*

11 YEARS AT JPL

IN SITU Instruments

AT THE MOST BASIC molecular level, all life on Earth is fundamentally the same, constructed from a relatively small set of chemical building blocks. By analyzing the distributions of organic molecules on other worlds, we can search for patterns of these building blocks that can provide clues about the presence of extinct or extant life. In this search for life in the universe, instrumentation capable of liquid-based chemical analysis is needed. This requirement for liquid analysis is not surprising: it was in water that life evolved on Earth and through liquid-based techniques that we have greatly augmented our understanding of biology and complex biological processes.

Microchip electrophoresis with laser-induced fluorescence (ME-LIF) detection is a liquid-based technique that provides efficient separations for a variety of these building blocks such as amino acids or fatty acids. Specific molecular properties of these organic acids (chirality of amino acids, and carbon chain length of fatty acids) are useful biomarkers should they be detected in extraterrestrial environments. Towards this goal, JPL has developed the Chemical Laptop, the first battery-powered, automated, reprogrammable, portable astrobiology instrument. The Chemical Laptop houses the microfluidics, electronics, and optics needed to perform highly sensitive ME-LIF analysis of organic acids and other organic biomarkers. »

BIG SCIENCE in a Small Package

JPL HAS DEVELOPED "lab-on-a-chip" systems to search for signatures of past or present life on alien worlds. These miniature laboratories could be placed aboard future spacecraft or planetary rovers that could search for chemical biosignatures in places where astronauts cannot yet visit. These miniature laboratories could do all the experiments required in an automated fashion, without needing a human present. These automated lab-on-a-chip systems are made of stacked glass wafers that are no larger in circumference than a DVD. The microchip seen here was designed, fabricated, and tested at the JPL MDL. It integrates an array of microvalves for fluidic manipulations with a microchannel for electrophoretic separation and detection for analysis of the organics in a given sample. This device was used to perform for the first time an entire "end-to-end" analysis of amino acids in an automated fashion; that is, all the steps for the analysis were executed by sending commands to the microchip from a computer without requiring any human intervention.

This technology allows for programmable analyses and is extremely useful for planetary missions to places such as Mars, Europa, Enceladus, or Titan, where the samples encountered may be very different than anticipated. In addition to extraterrestrial exploration, this technology also has multiple applications on Earth, such as environmental monitoring and clinical analysis in remote settings, where portable instrumentation would be useful. ■

A picture of the first prototype microchip developed at MDL for automated analysis of amino acids. This technology could be used to find microscopic forms of life on other planets. This would be essential not only for astrobiology, but also to keep future astronauts safe as they explore Mars and other worlds.

SEARCHING FOR LIFE in the Universe

THE SEARCH FOR EVIDENCE of past or present life on alien worlds starts with the detection of organic signatures essential for life on Earth. Towards this end, JPL has developed a new strategy for analyzing fatty acids on our microfluidic devices.

Fatty acids are found in the cell membranes of all three kingdoms of life on Earth and normally account for 5–10% of microbial biomass. Thus, by analyzing these molecules it would be possible to identify the remains of microorganisms present in extraterrestrial samples.

Terrestrial microorganisms have cell membranes with different carbon chain length signatures. For example, algal fatty acids tend to be around the C20/C22 mark whereas bacterial fatty acids are typically C16/C18 in length. Our microfluidic analyzer distinguishes a broad range of fatty acids by the length of their carbon chains. Thus, by measuring these molecules in an unknown sample, we can gain information about what organisms were present, even if the sample is very old and the organisms are no longer alive.

In 2014, MDL demonstrated the analysis of the full range of short to long fatty acids (C2–C30) for the first time on a microfluidic device (**IMAGE A**). A new fluorescent dye was used to label the carboxylic acid in a two-step, one-pot reaction to enable detection via laser-induced fluorescence. Fatty acids were successfully detected in a sediment sample from the Snake Pit hydrothermal system of the Mid-Atlantic Ridge (**IMAGE C–D**), demonstrating the potential of this method to help characterize microbial communities through targeted biomarker analysis. ■

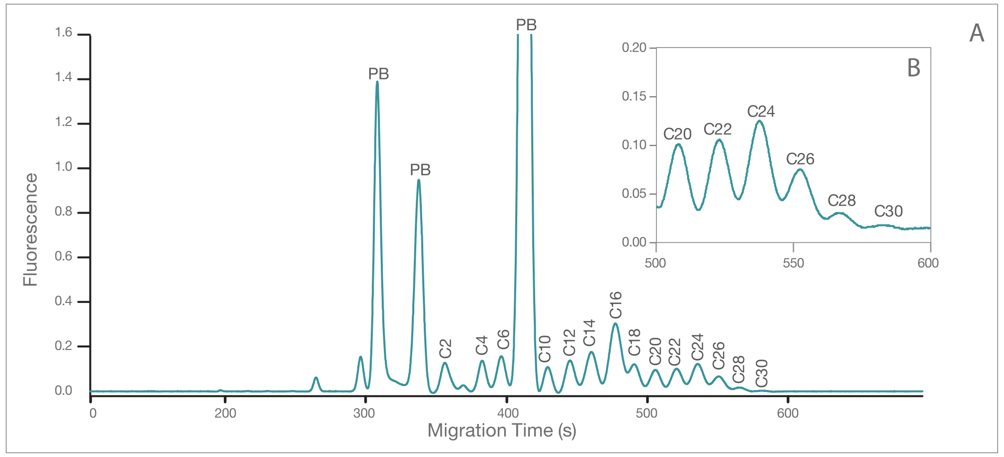
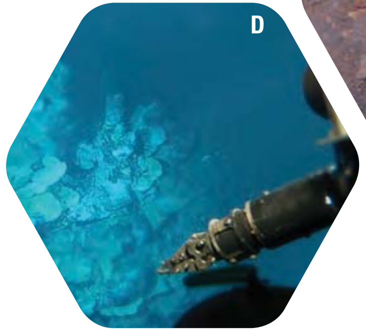


IMAGE A: Separation of C2 to C30 fatty acids (2 mM C2–C26, in ethanol on a microchip. **IMAGE B:** Long-chain fatty acids. **IMAGE C:** Sample collection at the base of the mound. Solid rocks were collected with the manipulator and sediments were collected with a water vacuum connected to a sample chamber. **IMAGE D:** The Snake Pit hydrothermal vent field as seen from the MIR 2 submersible. Active vents can be seen at the top of the structure. The sample site was at the base.



TAKING THE LAB to the Sample

DURING THE LAST DECADE, JPL has made great progress towards the development of portable instruments for in situ detection of organics. The MDL instrument combines microchip electrophoresis (ME) with laser-induced fluorescence (LIF) detection for a powerful technique that allows the analysis of a wide range of relevant biomarkers with extreme sensitivity. JPL is pushing this technology forward with the goal of one day implementing ME-LIF on a future spaceflight mission. MDL has developed the current state-of-the-art instrument integrating ME-LIF detection and automation capabilities: the Chemical Laptop.

The Chemical Laptop is capable of performing liquid-based analysis of multiple samples in an automated fashion in the field. This truly portable instrument is also extremely sensitive, allowing the detection of traces of organic molecules that could be present on Europa or other destinations in the solar system. This year, the instrument was tested for the first time outside the laboratory by performing analysis on amino acids in green rust. The Chemical Laptop was placed on top of a rover in the Mars Yard at JPL as proof of concept. ■

DEVELOPMENT OF A MICROFLUIDIC CHEMICAL ANALYZER
from the Atacama to the Mars Yard and the Bottom of the Ocean

'05 — Field test in the Atacama Desert of a microfluidic instrument and extraction unit developed at UC Berkeley in collaboration with JPL. Extracts of samples from the Yungay Hills were analyzed, detecting amino acids down to 4 ppb.

'07 — The Urey Instrument was selected for the ESA ExoMars Mission. While Urey was descoped from the payload in 2009 before a working prototype could be built, the project concept was advanced, eventually becoming the Chemical Laptop.

'09 — First demonstration of automated analysis of amino acids on a microchip developed at MDL.

'11 — Development of a Teflon membrane for incorporation into microfluidic devices. These membranes are resistant to organic solvents and reduce the possibility of contamination.

'12 — Design of a 3-D instrument model for the Planetary In Situ Capillary Electrophoresis System (PISCES). PISCES integrates an extraction subsystem with the ME-LIF analyzer. PISCES could readily be incorporated into planetary landers, rovers, or other robotic exploration vehicles.

'12 — New strategies for analysis of sulfur-containing molecules were developed and validated by analyzing fluid from geothermal pools.

'13 — New protocols for detection of long-chain amines were demonstrated by analyzing Titan aerosol simulants (tholins).

'14 — First analysis of fatty acids on a microchip using organic solvents was performed at MDL.

'15 — The Chemical Laptop was tested for the first time in the field. The instrument was operated at the Mars Yard for four hours using only battery power.

The Snake Pit hydrothermal vent field as seen from the MIR 2 submersible. Active vents can be seen at the top of the structure.

CREDIT : K. P. Hand

What Happens NEXT

CURRENT research is focused on incorporating additional features to the existing Chemical Laptop, such as the capability of looking at solid samples and performing pre-concentration on-chip. **IMAGE C** shows the first demonstration of manipulation of sediments on-chip. We modified the microfluidic architecture to integrate a filter and confined the sample to one section of the microchip. This proof of concept is a simple demonstration of how this technology could be used to perform extractions on-chip. Following extraction, the sample could be routed to another area of the microchip for pre-concentration employing trapped beads (**IMAGE B**).

JPL is also developing new methods for the analysis of chiral amino acids on-chip. ■

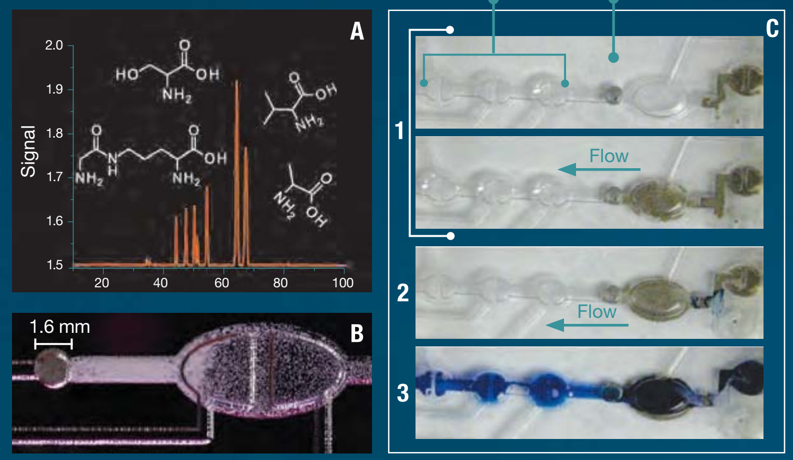


IMAGE A: Example of an analysis of amino acids on-chip. Current research involves chiral analysis of amino acids. **IMAGE B:** Picture of glass microbeads (~40 to 60 μm) trapped inside a microfluidic device for pre-concentration. **IMAGE C:** First demonstration of manipulation of solid samples on-chip. [1: Pumping sediment mixed with blue dye into the device, 2: Pumping water through the sediment, 3: Water dissolves the dye mixed with the sample].

MDL requires complex integrated building systems.

Semiconductor processing equipment in MDL's cleanrooms are utilized by researchers to fabricate improved sensors for instrumentation.

"MDL equipment is **often custom built** to specific requirements."

JAMES LAMB
Lead,
Facility and Safety

30 YEARS AT JPL

Infrastructure & CAPABILITIES

THE SOPHISTICATED SEMICONDUCTOR processing that takes place in the MDL requires complex integrated building systems and equipment. These closely monitored state-of-the-art capabilities installed in ultraclean environments form the foundation of MDL's technical implementation and innovation. Oversight and local configuration control is provided by the Central Processing and MDL Support Group, which also maintains a small staff of processing personnel for specialized processing support. Direct services are managed, coordinated, and provided in maintaining the building infrastructure and equipment, including life safety systems for safety assurance. While industrial "fabs" are usually designed for mass production of devices using a single set of standard processes, operations in MDL are much more flexible, allowing research, development, and small-scale production of a broad range of devices, wafer sizes, wafer thicknesses, and material families. MDL processes involve Si, GaAs, GaN, and superconducting materials. As a result, MDL equipment is often custom built for specific requirements. Despite this flexibility and the diverse operations, sufficient controls are in place to also allow processing of flight deliverables, and MDL has a long track record of successfully doing this. Over the last quarter of a century of MDL's operations, numerous infrastructure systems in MDL have not only been maintained, but also have been renewed and upgraded to maintain its cutting-edge capabilities. »

MDL's Process Cooling Water System, one of the many building infrastructure systems which support operations in MDL.

SIGNIFICANT MDL INFRASTRUCTURE RENEWALS

OVER THE LAST 25 YEARS

- Replacement of the Life Safety Monitoring systems
- Upgrade and expansion of the RO/DI water plant
- Replacement and upgrade of the process cooling water system
- Replacement and upgrade of the compressed dry air system
- Replacement of the house vacuum pumps
- Expansion of the LN2 coolant feed system
- Addition of an annex building with characterization labs
- Replacement and upgrade of the emergency generator
- Redesign of the main air intake to reduce nuisance sound and improve humidity control
- Addition of two new cleanroom air handlers (AH5 and AH6) to improve heating, ventilating, and air conditioning (HVAC) control
- Redesign of the inorganic wet ccrubber and blowers to improve performance, reduce blow-by, and enhance servicing
- Addition of electrical power feeds
- Expansion of the cleanrooms to the north side of the first floor
- Roof replacement and building seals renewal
- Addition of solar panels to the roof
- Addition of variable speed controls to the cleanroom recirculating units (RCUs) to allow energy savings by reducing air flows in off hours
- Replacing cleanroom High Efficiency Particulate Absorption (HEPA) air filters twice

Equipment within MDL has also been maintained, renewed, and expanded with major changes and investments in the areas of sample preparation, patterning, deposition, etching, characterization, and packaging. Of particular note over the last 25 years were A) Updating the etching capability with ICP sources (qtn. 5); B) Expanding patterning capability through stepper (qtn. 3) and automated spin coater (qtn. 3) additions, as well as updating e-beam lithography capability; C) Adding load lock deposition systems and investing in both CNT growth furnaces, updated LPCVD capability, and ALD capabilities; D) Updating characterization capability in numerous areas; E) Enhancing packaging capability through adding flip chip bonders, a specialized Parylene coater, and updated dicing capabilities; and F) Increasing multiple wafer diameter processing capabilities to handle larger wafer sizes. (*MDL can process 3-inch, 4-inch, 6-inch, 8-inch, and some 9-inch diameter wafers as well as pieces.*)

Such updates, renewals, and investments are done continually on an annual basis with prioritizations established by need and available resources in accordance with a five-year investment plan. ■

IN 2014, MDL MADE THE FOLLOWING EQUIPMENT ACQUISITIONS, UPGRADES, AND CHANGES:

1. **PlasmaTherm APEX SLR Fluorine-based Inductively Coupled Plasma (ICP) Etcher with Laser End Point Detector.** This system provides expanded precision etching capability in MDL allowing the separation of deep and shallow etches and improved control and repeatability. In order to free up footprint space to install this system, the Plasmaster RME 1200 Chlorine Reactive Ion Etcher (RIE) with glovebox was removed.
2. **PlasmaTherm Versaline Chlorine-based Inductively Coupled Plasma (ICP) Etcher** for III-V materials. This system with enhanced capability replaced a PlasmaTherm ECR 770 Chlorine RIE.
3. **Angstrom Engineering Indium – Metal Evaporator** This system allows thermal evaporation of Indium bumps for bump bonding and in situ e-beam evaporation of other metals to passivate and change the wetting properties of in situ deposited coatings.
4. **Refurbished Suss RC8 Spin Coater.** This system provides dedicated capability for resist depositions for IR photonics applications.
5. **Zygo ZeMapper**, a non-contact 3-D Profiler for characterizing micro- and nano-feature optical components and focal plane arrays (FPAs).
6. **Custom Superconducting Material Device Deposition System.** This existing system from another lab was retained and relocated to the MDL annex to allow the deposition of new test structures.
7. **Capabilities were enhanced through:** A) the acquisition of a refurbished Varian Auto-test 947D Leak Detector; B) the purchase of two (2) Honeywell FLEX portable toxic gas monitors with data logging capabilities for the detection of hydrides and mineral acids; C) the design and fabrication of two exhausted in-use photoresist cabinets; D) the purchase of a new flammable refrigerator freezer for the storage of the increased variety of photoresists in use in MDL; and E) the upgrade of syringes and dispense canisters in the Solar Semi Spin Coater system.

IN ADDITION, IN 2014, BESIDES STANDARD ONGOING FACILITIES MAINTENANCE UPKEEP, OTHER FACILITY INFRASTRUCTURE RENEWALS WERE IMPLEMENTED:

1. A new centralized water maintenance contract was specified, negotiated, issued, and transitioned.
2. A new gate arrangement for the MDL equipment yard was implemented due to the new JPL parking structure.
3. A new LN2 control interface for the Veeco GEN200 (8-inch) Si MBE was designed and installed to allow shutdown of the growth operation in the event of a phase separator malfunction.
4. New carpeting was installed in the MDL first floor display area / exit corridor 302-100.

Significant participation in outreach / marketing activities was also accomplished in 2014 with:

a. More than 80 MDL individual tours given throughout the year.

b. More than 14,000 visitors physically counted as accessing the building and viewing the MDL displays during the two days of the JPL Open House on October 11 and 12, 2014.

c. Taking and giving to the public more than 2,500 IR photographs with MDL-developed IR cameras during the JPL/MDL Open House event.

MDL FACILITY & SAFETY SYSTEM MILESTONES

MDL FORMULATION, CONSTRUCTION, AND START-UP

1982 Concept of Advanced Microelectronic Program (AMP) formulated (an R&D center to fill the gap between universities and industry for NASA's needs).

1985 SEPTEMBER: 100% Study Phase for JPL's Microdevices Laboratory completed and submitted to NASA through CoF Process. Approved and congressional line item funding obtained.

1986 Detailed construction specifications and plans for MDL, Building 302, completed 6/20/1986; (Addendums 2/04/1987).

1987 JANUARY: Center for Space Microelectronics Technology (CSMT) established (to create a multi-agency critical mass program with staff, facilities, and equipment). MDL construction begins.

1988 AUGUST: First annual employee safety and semiconductor chemical operations training completed. OCTOBER: Base building construction completed. Building dedicated; offices occupied. DECEMBER: Phase 1, Informal Safety Review conducted.

1989 FEBRUARY: MDL Completion Project established with two phases: 1) Fit-up: safety equipment (purchase, installation). Move and clean equipment. 2) Hook-up: acceptance and check-out. MARCH: MDL Safety Advisory Board established. May: Hook-up Blue Books completed. AUGUST: Construction fit-up and hook-up completed. MDL safety plans in place. First RMPP submission. Phase 2 Formal MDL Safety Review (Liens and RFAs addressed, Operational Readiness Process established). SEPTEMBER: Final Report Issued. Non-toxic operations begin.

1990 APRIL: RMPP approved. 24-hour JPL Fire Dept. and Haz Mat Response Team trained and in place. **Full operations begin**.

MDL OPERATIONAL ACTIVITIES / CHANGES

1992 Replaced controlled combustion decomposition oxidation (CDO) units for MOCVDs with Aixtox wet scrubber units. Incipient fire detection system added.

1993 RMPP updated. (Dichlorosilane and 50% AsH3 bal. H2 added—SCAQMD approves). Improved inorganic exhaust wet scrubber and inorganic exhaust operation through upgrades.

1994 HEPA/ULPA Filters replaced in MDL cleanrooms. RO2 and water recovery system installed and verified on MDL DI water plant. Inorganic exhaust upstream damper units replaced with new units having external serviceable bearings. Added second seismic control system.

1995 MDL's emergency generator fuel tank replaced. MDL entry tiles ground with circles to eliminate slipping hazard when wet. Manual shut-down switches added to MDL control room. JPL Engineering Council Review of the MDL Safety Assurance Maintenance Requirements.

1996 Reorganization of MDL Safety Engineer reporting from Section Manager to MDL Manager. Inorganic exhaust upstream damper assemblies removed and valved drain system added.

1997 RMPP program subsumed by CalARP and RMP program. JPL and not MDL defined as facility. JPL (incld. MDL) falls below threshold limits requiring formal RMP program plan.

1998 100% Arsine replacement of 50% AsH3 bal. H2 requested. Dispersion analysis done. SCAQMD approves.

1999 Hydrogen Distribution Bunker 302-155 constructed. Veltron air flow measurement systems installed — AH1-cleanrooms, 302-153, and AH4.

2000 Added cleanroom 302-101A and connection from 302-119; AH-5; AH-6; 300KVA transformer; e-beam lithography UPS system; and DI water plant RO2 upgrade. Y2K replacement of MDA 7100 toxic gas monitors with CM4 units. NASA OEB. Review of MDL Operations.

2001 MDL machine shop 302-149 lab conversion. Fire hoses removed from building 302 (Fire Dept. connections retained). AH1 Cool Fog humidity control upgrade added. MDL alarm point review and testing. MDL DI Water Plant RO2 revision/upgrade.

2002 Air intake to AH1 modified for noise reduction to surrounding community. MDL fire system sprinkler heads reviewed and renewed. Full medical exams with blood work discontinued for MDL H-6 processors.

2003 MDL DI water plant RO3 installed.

2004 Stepper install mods completed in 302-119. MDL Annex construction started. Prototype solvent processing system designed, fabricated, and installed. First-floor north panel displays updated (phase 1). MDL Safety Support restructured, eliminating 1 of 3 Safety Engineers.

2005 MDL Annex/Addition occupancy. Fire smoke detector system upgraded to laser detection system. Laptop wireless Wi-Fi repeater installed. Light Labs 302-105B, 302-105C, and 302-106 merged to form new suite. First-floor north panel displays updated (phase 2).

2006 AH1 modified for improved humidity control. AH1 blower replaced. Secondary containment increased on MDL's emergency generator fuel tank.

2007 Replaced MDA toxic gas monitoring systems with Honeywell Vertex System; MDI Supervisory System with Notifier system and NASA centralized Lenel system; south inorganic exhaust blower wheel; and first-floor carpeting. Upgraded MDL cleanroom lighting. Second-floor lobby display updated and projector added.

2008 Replaced north inorganic exhaust blower wheel. MDL roof replaced. 30-kW solar panels added. Second-floor carpets replaced.

2009 Replaced MDL cleanroom HEPAs; IFD panels; and first-floor angled displays. Raised ceiling for 8-inch Si MBE. Added 45 KVA transformer; and variable speed drives to RCUs. Upgraded process cooling water system. NASA OEP Review of MDL.

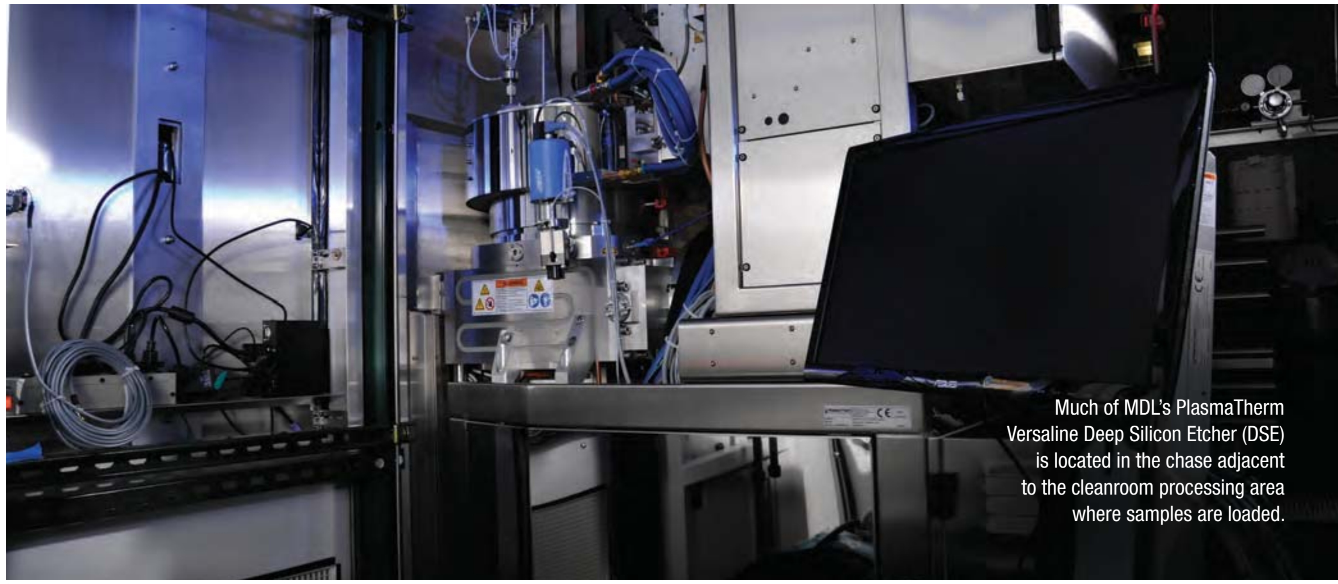
2010 Added cell phone repeaters; electrical panel locks; and humidity and process cooling water temperature monitors with alarm state notifications. Replaced / upgraded RO/DI water pre-filtration plant; and CDA system. Renewed external facing seams. Purchased spare AH1 blower.

2011 Created local O_2 deficiency evacuation zones; an increased number of door alarm zones; and more IFD points. Added 2 NF_3 and 1 portable combustible detectors; plus major Vertex spares. Rebuilt O_2 manifold; inorganic exhaust blower motors; and replaced the demister elements.

2012 VOIP lab phones installed. DI/RO water plant HW and sequencing upgraded. AH1 humidification system upgraded. 302-101 Class 100 (ISO 5) cleanroom conversion. Bypass plumbing added to process cooling water system for servicings. Emergency generator replaced (350 kW to 500 kW).

2013 MDL Annex cryo dewar staging area added with improved drainage. The Notifier Life Safety System software was rewritten and more safety monitoring sensors installed. Improved energy management MDL RCU monitoring system installed. Updated JACE environmental control system interface installed.

2014 First-floor carpeting replaced. Two portable Honeywell "FLEX" toxic gas monitors added. Two custom exhausted in-use photoresist cabinets added. Flammable refrigerator/freezer for the storage of in-use photoresists added. More cell phone repeaters added.



Much of MDL's PlasmaTherm Versaline Deep Silicon Etcher (DSE) is located in the chase adjacent to the cleanroom processing area where samples are loaded.

An MDL processor in cleanroom garb loads silicon wafers into MDL's Canon EX6 Stepper.

MDL EQUIPMENT COMPLEMENT MILESTONES

ADDITIONS AND DELETIONS

1991 ADDITIONS
- AIXTRON MOCVD
- Branson Plasma Asher
- Custom Contact Alloyer

DELETIONS
- NAVTEC MOCVD
- Tegal Plasma Asher

1992 ADDITIONS
- CALEB Quantum Dot Aerosol MOCVD
- Two (2) Semitool 270S Spin Rinser Dryers (SRDs) with ionization

DELETIONS
- Custom LACVD

1993 ADDITIONS
- Varian 960D Leak Detector
- Surface Science SSX-501 XPS Upgrade
- Custom Lesker Chemically Assisted Ion Beam Etcher (CAIBE)
- Digital Instruments Nanoscope IIIA Atomic Force Microscope (AFM)

DELETIONS
- Alzeatek LPE 1
- Alzeatek LPE 2
- Veeco Leak Detector

1994 ADDITIONS
- STS Deep Trench Reactive Ion Etcher (DRIE)
- Alphastep 250
- DISCO 320 Wafer Dicing Saw
- Phillips MRD Four Circle X-Ray Diffractometer
- Horizontal Tube Cleaner with Chemical Reclaim
- Riber EVA 320 Si MBE Upgrade to Pseudo 4-inch capability
- GCA Mann Wafer Stepper with Custom Stage Allowing Different Sizes and Thicknesses of Wafers Housing and Computer Upgrade
- ZYGO Interferometer for Microsensor/Microinstrument Characterization
- Atmospheric Pyrogenic Oxidation System
- Mars Seismometer Characterization Facility in 302-101
- LIGA Beamline at Stanford Linear Accelerator
- Cleanroom Probe Station IV/CV Measurement Upgrade
- SiO Thermal Evaporator
- MCS Plasma System Plasmaster RME-1200 Fluorine RIE
- MCS Plasma System Plasmaster RME-1200 Chlorine RIE

DELETIONS
- Laser Curtain and Optical Test Set-up from 302-147
- CO2 and Excimer Lasers for MBEs
- Deep-Level Transient Spectroscopy (DLTS) System
- Two (2) Thermco Spartan 2-inch dia Wafer Furnace 3-stacks
- Sloan Profilometer
- Tempress Saw
- Two (2) Gaertner Manual Ellipsometers

1995 ADDITIONS
- TSC Evaporator
- Oriel 6-inch Flood Exposure System
- MSC Plasmaster Fluorine RIE
- Die Attach Laser Fabrication Equipment
- Electronic Visions Wafer Bonder
- Modification of Riber 2300 III-V MBE System for GaN/AIN Growth
- Polytec Single Fiber LDV System for MicroGyro Characterization
- WYKO RST Plus Surface Measurement System

DELETIONS
- ULTEK Evaporator
- Tamarak UV 3-inch Flood Exposure System
- Plasma-Tech Cl2 RIE
- Removal of Spin Rinser Dryers from Acid Benches

1996 ADDITIONS
- New Acid Wet Bench to 302-153
- Residual Gas Analyzer (RGA) upgrade to MOCVD
- Solitec Spin Developer
- UV Measurement Setup
- Vacuum FTIR for Far IR
- Ball Bonder
- Nikon Cleanroom Inspection Microscope
- PlasmaTherm PECVD
- Linked Evaporators for MOx follow-on
- Sloan 1 and 2 SL1800 Evaporator Upgrades
- PlasmaTherm ECR Chlorine RIE

DELETIONS
- IAS Acid Wet Bench from 302-153
- Manual Ellipsometer

1997 ADDITIONS
- New Commonwealth IBE-80 Ion Mill
- Modutrac in-line additions to MBEs
- Circuit Board Prototyping System (μ-milling machine)
- JEOL JBX-5DII 10MHz Pattern Generator Upgrade
- Submicron Prober System with Analysis Electronics
- Modular Process Technology RTP 600S Rapid Thermal Annealer

DELETIONS
- Old Commonwealth Ion Milling System

1998 ADDITIONS
- Thomas Swan MOCVD
- Vertical Tube Cleaner
- Frontier Semiconductor FSM 128 Film Stress and Wafer Flatness Measuring System
- EX3 Stepper Computer Upgrade
- Fiber Optic Laser Welding and Alignment Equip
- LIGA Beamline Upgrades at Stanford Linear Accelerator

DELETIONS
- CALEB Quantum Dot Aerosol MOCVD
- Custom A-Chamber Sputtering system
- General Air MOCVD
- Horizontal Tube Cleaner

1999 ADDITIONS
- Sentech SE 850 Multispectral Ellipsometer

DELETIONS
- Akashi Beam Technology ABT-002B TEM

2000 ADDITIONS
- Karl Suss BA6 Contact Aligner
- Karl Suss BA6 Bonder
- S-Parameter Analyzer
- Color CCD Camera and Critical Dimension Upgrade for Zeiss microscope
- Six-Inch Diffusion Furnace Upgrade
- Three (3) CM4 Local Toxic Gas Monitors with Data Logging

DELETIONS
- Electronic Visions Aligner
- Cambridge Stereo Scan 100 SEM
- Three MDA 7100 Local Toxic Gas Monitors (Y2K issue)

2001 ADDITIONS
- JEOL 9300 FS E-Beam Lithography System
- Disco 321 Wafer Dicing Saw
- Photoluminescence Mapping System
- Load-Locked CVC Sputtering System
- Upgrade of Nanoscope IIIA AFM to Digital Instruments Dimension 5000 AFM with Stage and Head Replacement
- Tousimis Critical Point Dryer
- Two Mesa West Inc. 3-station Electroplating Benches
- Spare Chamber Upgrade for STS DRIE
- Hutch and Scanner for LIGA Beamline at Standford Linear Accelerator

DELETIONS
- JEOL JBX-5DII E-Beam Lithography System
- Microautomation Saw
- Circuit Board Prototyping System (μ-milling machine)

2002 ADDITIONS
- Epi GEN III Antimonide Molecular Beam Epitaxy (MBE) System

DELETIONS
- None

2003 ADDITIONS
- TYSTAR 4-stack 100mm (4-inch) LPCVD with low stress Si3N4, Wet Pyrogenic Oxidation, Low-Temperature Oxide (LTO), and Doped PolySilicon tubes
- Ultra T Equipment SCSe Mask Cleaner
- Nikon inspection microscope with Critical Dimension and digital documentation capability

- Lesker Low-Loss Dielectric Deposition System
- Research Devices Bump Bonder
- Sentech SE 850 Multispectral Ellipsometer IR Upgrade

DELETIONS

- Rudolph Auto-El Automated Ellipsometer

2004 ADDITIONS

- Strasbaugh 6EC Chemical Mechanical Polisher (CMP)
- JEOL JSM-6700 Field Emission SEM with EDX
- Tyoda Serac prototype Solvent Glovebox Processing System with VOC capture
- Canon FPA3000 EX3 Stepper Projection Mask Aligner with EX4 Optics
- Unaxis Shuttleline Load-Locked Fluorine Inductively Coupled Plasma (ICP) RIE
- Unaxis Shuttleline Load-Locked Chlorine Inductively Coupled Plasma (ICP) RIE
- Suss MA-6 (UV300) Contact Mask Aligner
- Two (2) Optical Profilometers for photoresists and large wafers
- Loomis LSD-100 Scriber Breaker
- Site Services Spin Developer
- Tepla PP300SA Microwave Plasma Asher
- Finetech Fineplacer 96 “Lambda” Bump Bonder

DELETIONS

- Vertical Tube Cleaner
- JEOL IC848 LaB6 SEM
- Hummer Sputter Deposition System
- Karl Suss Diamond Scriber Breaker

2005 ADDITIONS

- Atomate CNT growth furnace
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System
- TYSTAR 6-inch LPCVD with two tubes for Low Stress Silicon Nitride and Atmospheric Wet/Dry Oxidation

DELETIONS

- AIXTRON MOCVD
- Akashi Beam Technology ABT-002B Transmission Electron Microscope (TEM)

2006 ADDITIONS

- AJA Load-Locked Metal Sputtering System
- AJA Load-Locked Dielectric Sputtering System

DELETIONS

- Load-Locked CVC Sputtering System
- Dual stack Semitool 270S Spin Rinser Dryer (SRD)

2007 ADDITIONS

- Suss Gamma Microlithgraphy 4-Module Cluster Cassette-to-Cassette Spin/Developer System
- Oxford Plasmalab System 100 Advanced ICP 380 HD PECVD
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System
- Oxford Phoenix ICP Chlorine RIE
- Temescal BJD FC-2000 E-Beam Evaporator for III-V devices
- Denton Infinity 22 Indium Evaporator
- HP Agilent 4155C Semiconductor Parameter Analyzer
- Subkelvin High-Throughput Cyrogenic Test Facility with 2 Dilution Refrigerators in 302-245
- GenISys Layout BEAMER Proximity Correction Software for JEOL JBX-9300FS Electron-Beam Lithography System
- Atomate Corp. Carbon Nanotube CVD Furnace System
- Advanced Communication Devices, Inc. Custom XeF2 Etch System
- Honeywell Analytics Inc. Vertex 72 Point Detection System
- YES HMDS Primer System
- VEECO WYKO Surface Measurement System

DELETIONS

- Custom Lesker Chemically Assisted Ion Beam Etcher (CAIBE)
- MicroScience ECR Dielectric Deposition System
- Two MDA Scientific System 16 Toxic Gas Monitoring units

2008 ADDITIONS

- Wafab International 96" RCA Polypropylene Wet Process Station for larger (150mm / 6-inch diameter) Wafers with Custom Waste Collection Cabinet
- Rhetech Inc. Semitool Spin Rinse Dryer 470S R
- Temescal Evaporator (Task Specific)
- Additional Pumps and Modules (incld. Mask Module) for Suss Gamma Microlithography 4-Module Cluster Cassette-to-Cassette Spin/Developer System

DELETIONS

- Old Integrated Air Systems, Inc. RCA Wet Bench
- CHASE-600-P p-Type Evaporator

2009 ADDITIONS

- LASAIR II 310A/B Airborne Particle Counter
- Veeco GEN200 (8-inch) Silicon Molecular Beam Epitaxy (MBE) System
- Silicon on Insulator (SOI) and Computer Software Upgrade to STS Deep-trench Reactive Ion Etcher (DRIE)
- Enhanced Radical Atomic Layer Deposition (ALD) Upgrade for Oxford Plasmalab 80 OpAL ALD System
- KLA-Tencor Surfscan 6220 Wafer Particle Monitor
- Olympus LEXT IR Confocal Microscope
- Suss Probe Station and Software Upgrade
- E-Beam Lithography Sample Holder Jigging Upgrade
- Digital Instruments Dimension 5000 AFM Computer and Software Upgrade

DELETIONS

- North Mesa West Inc. 3-Station Electroplating Bench
- PMS Particle Counter
- MOx Sample Entry Glove Box

2010 ADDITIONS

- SET FC-300 Flip-Chip Bump Bonder
- AJA Load-Locked Thermal Co-Evaporator
- Branson Plasma Asher (Backup)
- Lesker Superconductor Sputtering System 150 mm Wafer Diameter Chamber Upgrade
- AJA Load-Locked Evaporator
- Digital Instruments Dimension 5000 AFM table upgrade

DELETIONS

- JEOL 840F Field Emission SEM
- North Half of UHV Modutrac Assemblies and Gloveboxes from 302-147
- MOx Organic Evaporator
- MOx Testing glovebox (Reconfigured for Silane Experiment)
- HP XPS/ESCA System
- Riber 2300 Materials III-V MBE
- Zeiss Microphot III Metelograph Microscope System

2011 ADDITIONS

- PANalytical X Pert Pro Materials Research Diffractometer (MRD) with High-Temperature Stage X-ray Diffraction System
- Nanometrics Electrochemical Capacitance Voltage ECV Pro Profiler
- Ion Gun for Veeco E-Beam Evaporator

DELETIONS

- Sloan 1SL1800 Evaporator
- Phillips MRD Four Circle X-Ray Diffractometer
- Leitz interferometer

2012 ADDITIONS

- Beneq TFS-200 Atomic Layer Deposition (ALD) System
- SET North America Ontos 7 Native Oxide (Indium Oxide) Removal Tool
- Precitech Nanoform 250 Ultra Diamond Point Turning System
- Canon FPA3000 EX6 Deep Ultraviolet (DUV) Stepper Projection Mask Aligner
- Canon FPA3000 i4 i-Line Stepper Projection Mask Aligner
- New Wave Research EzLaze 3 Laser Cutting System
- Indonus HF VPE-150 Hydrofluoric Acid Vapor Phase Etcher
- SurfX 400L Atmospheric Surface Preparation System
- Horiba UVISEL 2 Ellipsometer System
- Measurement stand (FS10) and Computer Upgrade for FISBA uPhase 2 HR Compact Optical Interferometer
- SCS Labcoater 2 (PDS 2010) Parylene Coating System

DELETIONS

- Glasstec Solar ECR PECVD
- WYKO RST Plus Surface Measurement System
- Research Devices High Pressure Bump Bonder
- Tyoda Serac prototype Solvent Glovebox Processing System with VOC capture
- Mars Seismometer Characterization Facility from 302-101

2013 ADDITIONS

- Solitec 5110C Spin Coater
- PlasmaTherm Versaline Deep Silicon Etcher (DSE/DRIE)
- SolarSemi MC204 Microcluster Spin Coating System
- Semitool 870S Dual Spin Rinser Dryer
- Suss MA6 mask aligner MO Exposure Optics upgrade
- Frontier Semiconductor FSM 128-NT (200 mm) Manual Film Stress and Wafer Bow Mapping System
- Veeco WYKO NT9300 Optical Profiler 50X Upgrade

DELETIONS

- Solitec 5110-ND Spin Coater
- TYSTAR 4-stack 100mm (4-inch) LPCVD with low-stress Si3N4, Wet Pyrogenic Oxidation, Low-Temperature Oxide (LTO), and doped PolySilicon tubes

2014 ADDITIONS

- Suss RC8 Spin Coater
- PlasmaTherm APEX SLR Fluorine-based ICP RIE with Laser End Point Detector
- PlasmaTherm Versaline Chlorine ICP RIE for III-V Materials
- Angstrom Engineering Indium-Metal Evaporator
- Zygo ZeMapper
- Varian Auto-test 947D Leak Detector
- Two (2) Honeywell FLEX Portable Toxic Gas Monitors
- SolarSemi Spin Coater System Syringe and Dispense Canister Upgrades

DELETIONS

- Ultra T Equipment SCSe Mask Cleaner
- Plasmaster RME-1200 Chlorine RIE with glovebox
- PlasmaTherm ECR 770 Chlorine RIE

An MDL researcher loads a sample into MDL's Beneq atomic layer deposition (ALD) System.

APPENDICES

MDL EQUIPMENT COMPLEMENT

MATERIAL DEPOSITION

- Thermal Evaporators (6)
- Electron-Beam Evaporators (7)
- Angstrom Engineering Indium-Metal Evaporator
- Ultra-High-Vacuum (UHV) Sputtering Systems for Dielectrics and Metals (3)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Superconducting Materials (4)
- AJA Load Locked Thermal Co-Evaporator for Broadband IR Bolometer Depositions
- PlasmaTherm 790 Plasma Enhanced Chemical Vapor Deposition (PECVD) for Dielectrics
- Oxford Plasmalab System 100 Advanced Inductively Coupled Plasma (ICP) 380 High-Density Plasma Enhanced Chemical Vapor Deposition
  (HD PECVD) System for Low-Temperature Dielectric Growths
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System with Radical Enhanced Upgrade
- Beneq TFS-200 Atomic Layer Deposition (ALD) System
- Tystar (150-mm/6-inch) Low-Pressure Chemical Vapor Deposition (LPCVD) with 2 Tubes for
  - Low-Stress Silicon Nitride
  - Atmospheric Wet/Dry Oxidation
- Carbon Nanotube Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  - Veeco GEN200 (200-mm/8-inch) Si MBE for UV CCD Delta Doping (Silicon)
  - Veeco Epi GEN III MBE (Antimonide Materials)
  - Riber MBE for UV CCD Delta Doping (Silicon)
  - Riber Device MBE (GaAs)
- Thomas Swann Metallo-Organic Chemical Vapor Deposition (MOCVD) System

LITHOGRAPHIC PATTERNING

- Electron-Beam (E-beam) Lithography: JEOL JBX9300FS e-beam lithography system with a 4-nm spot size, 100,000-volt acceleration voltage, ability to handle wafers up to 9 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 7 mm of sag
- GCA Mann Wafer Stepper with custom stage allowing different sizes and thicknesses of wafers (0.7-µm res.)
- Canon FPA3000 i4 i-Line Stepper (0.35-µm res.)
- Canon FPA3000 EX3 Stepper with EX4 Optics (0.25-µm res.)
- Canon FPA3000 EX6 DUV Stepper (0.15-µm res.)
- Contact Aligners:
  - Karl Suss MJB3
  - Karl Suss MJB3 with backside IR
  - Suss MA-6 (UV300) with MO Exposure Optics upgrade
  - Suss BA-6 (UV400) with jigging supporting Suss bonder
- Wafer Track/Resist/Developer Dispense Systems:
  - Suss Gamma 4-Module Cluster System
  - Site Services Spin Developer System
  - SolarSemi MC204 Microcluster Spin Coating System
- Yield Engineering System (YES) Reversal Oven
- Ovens, Hotplates, Furnaces, and Manual Spinners (including 2 Solitec 5110C spinners, and a Suss RC8 Spin Coater)

DRY ETCHING

- Commonwealth IBE-80 Ion Mill
- Branson Plasma Ashers (2)
- Tepla PP300SA Microwave Plasma Asher

FLUORINE-BASED PLASMA ETCHING SYSTEMS

- STS Deep Trench Reactive Ion Etcher (DRIE) with SOI Upgrade
- PlasmaTherm Versaline Deep Silicon Etcher (DSE/DRIE)
- Unaxis Shuttleline Load-Locked Fluorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm APEX SLR Fluorine-based ICP RIE with Laser End Point Detector
- Plasmaster RME-1200 Fluorine RIE
- Plasma Tech Fluorine RIE
- STJ RIE for Superconductors
- Custom XeF2 etcher

CHLORINE-BASED PLASMA ETCHING SYSTEMS

- Unaxis Shuttleline Load-Locked Chlorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm Versaline Chlorine-based ICP Etcher
- Oxford ICP Chlorine RIE

WET ETCHING & SAMPLE PREPARATION

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (7)
- Rinser/Dryers for Wafers including Semitool 870S Dual Spin Rinser Dryer
- Chemical Hoods (7)
- Acid Wet Processing Benches (8)
- Tousimis 915B Critical Point Dryer
- Rapid Thermal Processors/Contact Alloyers (2)
- Polishing and Planarization Stations (5)
- Strasbaugh 6EC Chemical Mechanical Polisher
- Precitech Nanonform 250 Ultra Diamond Point Turning System
- SET North America Ontos 7 Native Oxide (Indium Oxide) Removal Tool
- SurfX 400L Atmospheric Surface Preparation System
- New Wave Research EzLaze 3 Laser Cutting System
- Indonus HF VPE-150 Hydrofluoric Acid Vapor Phase Etcher

PACKAGING

- SET FC-300 Flip Chip Bump Bonder
- Karl Suss Wafer Bonder
- Electronic Visions Wafer Bonder
- Finetech Fineplacer 96 “Lambda” Bump Bonder
- Thinning Station and Inspection Systems for CCD Thinning
- Wire Bonding
- DISCO 320 and 321 Wafer Dicers (2)
- Tempress Scriber
- Pick and Place Blue Tape Dispenser System
- Loomis LSD-100 Scriber Breaker
- SCS Labcoater 2 (PDS 2010) Parylene Coating System

CHARACTERIZATION

- Profilometers (2) (Dektak 8 and Alphastep 500)
- Frontier Semiconductor FSM 128 Film Stress Measuring system
- Frontier Semiconductor FSM 128-NT (200-mm/8-inch) Film Stress and Wafer Bow Mapping System
- FISBA µPhase 2 HR Compact Optical Interferometer
- Senetech SE 850 Multispectral Ellipsometer
- Horiba UVSEL 2 (190–2100 nm) Ellipsometer
- Dimension 5000 Atomic Force Microscope (AFM)
- KLA-Tencor Surfscan 6220 Wafer Particle Monitor
- JEOL JSM-6700 Field Emission SEM with EDX
- Nikon and Zeiss Inspection Microscopes with Image Capture (3)
- Olympus LEXT 3D Confocal Microscope
- Electrical Probe Stations with Parameter Analyzers (2)
- RPM2035 Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectroscopy
- PANalytical X’Pert Pro MRD with DHS High Temperature Stage X-ray Diffraction System
- Surface Science SSX501 XPS with Thermal Stage
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)
- Nanometrics ECV Pro Profiler
- VEECO / WYKO NT 9300 Surface Profiler (including 50X optics)
- Zygo ZeMapper non-contact 3D Profiler

JOURNAL PUBLICATIONS

1. T. Reck, C. Jung-Kubiak, J. Gill, and G. Chattopadhyay, "Measurement of Silicon Micromachined Waveguide Components at 500 to 750 GHz," *IEEE Trans. Terahertz Sci. Technol.*, 4 (1), 33, 2014.
2. A. Sergeev, V. Mitin, B. Karasik, and S. Vitkalov, "Ultrasensitive Superconducting Terahertz Detectors: Novel Approaches and Emerging Materials," *J. Phys.*: Conf. Ser. 486, 012021, 2014.
3. V. Mitin, V. Pogrebnyak, M. Shur, R. Gaska, B. Karasik, and A. Sergeev, "Hot-Electron Micro & Nanobolometers Based on Low-Mobility 2DEG for High-Resolution THz Spectroscopy," *J. Phys.*: Conf. Ser. 486, 012028, 2014.
4. C. B. McKitterick, H. Vora, X. Du, B. S. Karasik and D. E. Prober, "Graphene Microbolometers with Superconducting Contacts for Terahertz Photon Detection," *J. Low Temp. Phys.* 176, 291, 2014.
5. B. S. Karasik, C. B. McKitterick, and D. E. Prober, "Prospective Performance of Graphene HEB for Ultrasensitive Detection of Sub-mm Radiation," *J. Low Temp. Phys.* 176, 249, 2014.
6. J. V. Siles, C. Lee, R. Lin, G. Chattopadhyay, T. Reck, C. Jung-Kubiak, I. Mehdi, and K. Cooper, "A High-Power 105–120 GHz Broadband On-Chip Power-Combined Frequency Triple," *IEEE Microw. Wireless Compon. Lett.* DOI:10.1109/LMWC.2015.2390539, 2014.
7. E. Schlecht, J. V. Siles, C. Lee, R. H. Lin, B. Thomas, G. Chattopadhyay, and I. Mehdi, "Schottky Diode Based 1.2 THz Receivers Operating at Room Temperature and Below for Planetary Atmospheric Sounding," *IEEE Trans. THz Sci. Technol.* 6 (4), 661, 2014.
8. F. Boussaha, J. Kawamura, J. Stern, C. Jung-Kubiak, A. Skalare, and V. White, "2.7 THz Balanced Waveguide HEB Mixer," *IEEE Trans. THz Sci. Technol.* 4 (5) 545, 2014.
9. K. B. Cooper and G. Chattopadhyay, "Submillimeter-Wave Radar: Solid-State System Design and Applications," *IEEE Microw. Mag.* 15 (7), 51, 2014.
10. C. A. Leal-Sevillano, K. B. Cooper, E. Decrossas, R. J.Dengler, J. A. Ruiz-Cruz, J. R. Montejo-Garai, G. Chattopadhyay, and J. M. Rebollar, "Compact Duplexing for a 680-GHz Radar Using a Waveguide Orthomode Transducer," *IEEE Trans. Microw. Theory Tech.* 62 (11), 2833, 2014.
11. T. Reck, C. Jung-Kubiak, J. Siles, C. Lee, R. Lin, G. Chattopadhyay, I. Mehdi, and K. Cooper, "A Silicon Micromachined Eight-Pixel Transceiver Array for Submillimeter-Wave Radar," *IEEE Trans. THz Sci. Technol.* 5 (2), 197, 2015.
12. J. Hennessy, A. D. Jewell, H. F. Greer, M. C. Lee, and S. Nikzad, "Atomic Layer Deposition of Magnesium Fluoride via bis(ethylcyclopentadienyl)magnesium and Anhydrous Hydrogen Fluoride," *J. Vac. Sci. Technol.* A 33, 01A125, 2015.
13. P. Suvarna, J. Bulmer, J. M. Leathersich, J. Marini, I. Mahaboob, J. Hennessy, L. D. Bell, S. Nikzad, and F. Shahedipour-Sandvik. "Ion Implantation-Based Edge Termination to Improve III-N APD Reliability and Performance," *IEEE Photonics Technol. Lett.* 27, 498, 2015.
14. D. Z. Ting, A. Soibel, S. A. Keo, Sir B. Rafol, J. M. Mumolo, J. K. Liu, C. J. Hill, A. Khoshakhlagh, L. Höglund, E. M. Luong, and S. D. Gunapala, "Development of Quantum Well, Quantum Dot, and Type II Superlattice Infrared photodetectors," *J. Appl. Remote Sens.* 8 (1), 084998, 2014.
15. A. Soibel, C. J. Hill, S. A. Keo, L. Hoglund, R. Rosenberg, R. Kowalczyk, A. Khoshakhlagh, A. Fisher, D. Z.-Y. Ting, and S. D. Gunapala, "Room Temperature Performance of Mid-Wavelength Infrared InAsSb nBn Detectors," *Appl. Phys. Lett.* 105, 023512, 2014.
16. D.Z.-T. Ting, Y.-C. Chang, Sir B. Rafol, J. K. Liu, C. J. Hill, S. A. Keo, J. Mumolo, S. D. Gunapala, and S. V. Bandara, "The Sub-Monolayer Quantum Dot Infrared Photodetector Revisited," *Infrared Phys. Technol.*, http://dx.doi.org/10.1016/j.infrared.2014.09.028, 2014.
17. S. D. Gunapala, S. V. Bandara, J. K. Liu, J. M. Mumolo, Sir B. Rafol, D. Z. Ting, A. Soibel, and C. Hill, "Quantum Well Infrared Photodetector Technology and Applications," *IEEE J. Selected Topics in Quantum Electronics* 20 (6), 3802312, 2014.
18. L. Höglund, D. Z. Ting, A. Soibel, A. Fisher, A. Khoshakhlagh, C. J. Hill, S. Keo, and S. D. Gunapala, "Minority Carrier Lifetime in Mid-Wavelength Infrared InAs/InAsSb Superlattices: Photon Recycling and the Role of Radiative and Shockley-Read-Hall Recombination Mechanisms," *Appl. Phys. Lett.* 105, 193510, 2014.
19. L. Höglund, D. Z. Ting, A. Soibel, A. Fisher, A. Khoshakhlagh, C. J. Hill, S. Keo, and S. D. Gunapala, "Influence of the Carrier Concentration on the Minority Carrier Lifetime in Mid-Wavelength Infrared InAs/InAsSb Superlattices," *Infrared Phys. Technol.*, 2014. Published online: doi:10.1016/j.infrared.2014.10.011
20. A. Soibel, C. J. Hill, S. A. Keo, L. Hoglund, R. Rosenberg, R. Kowalczyk, A. Khoshakhlagh, A. Fisher, D. Z.-Y. Ting, and S. D. Gunapala, "Room Temperature Performance of Mid-Wavelength Infrared InAsSb nBn Detectors," *Infrared Phys. Technol.*, 2014. Published online: doi:10.1016/j.infrared.2014.09.030
21. S. D. Gunapala, S. B. Rafol, D. Z. Ting, A. Soibel, L. Höglund, C. J. Hill, A. Khoshakhlagh, J. K. Liu, J. M. Mumolo, and S. A. Keo, "1/f Noise QWIPs and nBn Detectors," *Infrared Phys. Technol.*, 2014. Published online: doi:10.1016/j.infrared.2014.09.031
22. S. Forouhar, C. Borgentun, C. Frez, R. M.Briggs, M. Bagheri, C. L. Canedy, C. S. Kim, M. Kim, W. W. Bewley, C. D. Merritt, J. Abell, I. Vurgaftman and J. R. Meyer, "Reliable Mid-Infrared Laterally-Coupled Distributed-Feedback Interband Cascade Lasers," *App. Phys. Lett.* 105, 051110, 2014.
23. R. M. Briggs, C. Frez, C. E. Borgentun, and S. Forouhar, "Regrowth-Free Single-Mode Quantum Cascade Lasers with Power Consumption Below 1 W," *App. Phys. Lett.* 105, 141117, 2014.
24. C. Borgentun, C. Frez, R. M. Briggs, M. Fradet, and S. Forouhar, "Single-Mode High-Power Interband Cascade Lasers for Mid-Infrared Absorption Spectroscopy," *Opt. Express* 23, 2446, 2015.
25. M. L. Cable, S. M. Hörst, C. He, A. M. Stockton, M. F. Mora, M. A. Tolbert, M. A.Smith, and P. A. Willis, "Identification of Primary Amines in Titan Tholins Using Microchip Nonaqueous Capillary Electrophoresis," *Earth Planet. Sci. Lett.* 403 (0), 99, 2014.
26. M. L. Cable, A. M. Stockton, M. F. Mora, K. P. Hand, and P. A. Willis, " Microchip Nonaqueous Capillary Electrophoresis of Saturated Fatty Acids Using a New Fluorescent Dye," *Anal. Method.* 6 (24), 9532, 2014.
27. E. T. da Costa, M. F. Mora, P. A. Willis, C. L. do Lago, H. Jiao, and C. D. Garcia, "Getting Started with Open-Hardware: Development and Control of Microfluidic Devices," *Electrophoresis* 35 (16), 2370, 2014.
28. A. D. Beyer, M. D. Shaw, F. Marsili, M. S. Allman, A. E. Lita, V. B. Verma, G. V. Resta, J. A. Stern, R. P. Mirin, S. W. Nam, and W. H. Farr, "Tungsten Silicide Superconducting Nanowire Single-Photon Test Structures Fabricated Using Optical Lithography," *IEEE Trans. Appl. Supercond.* 25 (3), 1, 2015.
29. A. D. Beyer, M. E. Kenyon, B. Bumble, M. Runyan, P. E. Echternach, W. A. Holmes, J. J. Bock, and C. M. Bradford, "Comparing Transition-Edge Sensor Response Times in a Modified Contact Scheme with Different Support Beams," *J. Low Temp. Phys.* 176 (3–4), 299, 2014.
30. M. E. Kenyon, A. D. Beyer, B. Bumble, P. E. Echternach, W. A. Holmes, and C. M. Bradford, "Toward a Detector/Readout Architecture for the Background-Limited Far-IR/Submm Spectrograph (BLISS)," *J. Low Temp. Phys.* 176 (3–4), 376, 2014.
31. M. A. Lindeman, "Resonator-Bolometer Theory, Microwave Read Out, and Kinetic Inductance Bolometers," *J. Appl. Phys.* 116 (2), 024506, 2014.
32. M. A. Lindeman, J. A. Bonetti, B. Bumble, P. K. Day, B. H. Eom, W. A. Holmes, and A. W. Kleinsasser, "Arrays of Membrane Isolated Yttrium-Barium-Copper-Oxide Kinetic Inductance Bolometers," *J. Appl. Phys.* 115 (23), 234509, 2014.
33. M. A. Lindeman, B. H. Eom, P. K. Day, L. J. Swenson, R. Wernis, H. G. LeDuc, and J. Zmuidzinas, "AC Bolometer Theory and Measurements of Kinetic Inductance Bolometer-Resonators," *J. Low Temp. Phys.* 176, 2014; 511, 2014.
34. C. Lee, Z. Zhang, G. Steinbrecher, H. Zhou, J. Mower, T. Zhong, L. Wang, X. Hu, R. D. Horansky, V. B. Verma, A. E. Lita, R. P. Mirin, F. Marsili, M. D. Shaw, S. W. Nam, G. W. Wornell, F. N. C. Wong, J. H. Shapiro, and D. Englund, "Entanglement-based Quantum Communication Secured by Nonlocal Dispersion Cancellation," *Phys. Rev. A* 90, 062331, 2014.
35. V. B. Verma, B. Korzh, F. Bussières, R. Horansky, A. E. Lita, F. Marsili, M. D. Shaw, H. Zbinden, R. P. Mirin, and S. W. Nam, "High-Efficiency WSi Superconducting Nanowire Single Photon Detectors Operating at 2.5 K," *Appl. Phys. Lett.* 105, 122601, 2014.
36. F. Bussières, C. Clausen, A. Tiranov, B. Korzh, V. B.,Verma, S. W. Nam, F. Marsili, A. Ferrier, P. Goldner, H. Herrmann, C. Silberhorn, W. Sohler, M. Afzelius, and N. Gisin, "Quantum Teleportation from a Telecom-Wavelength Photon to a Solid-State Quantum Memory," *Nat. Photonics* 8, 775, 2014.
37. D. R. Hamel, L. K. Shalm, H. Hübel, A. J. Miller, F. Marsili, V. B. Verma, R. P Mirin, S. W. Nam, K. J. Resch, and T. Jennewein, "Direct Generation of Three-Photon Polarization Entanglement," *Nat. Photonics* 8, 801, 2014.
38. R. Valivarthi, I. Lucio-Martinez, A. Rubenok, P. Chan, F. Marsili, V. B. Verma, M. D. Shaw, J. A. Stern, J. A. Slater, D. Oblak, S. W. Nam, and W. Tittel, "Efficient Bell State Analyzer for Time-Bin Qubits with Fast-Recovery WSi Superconducting Single Photon Detectors," *Opt. Express* 22, 24497, 2014.
39. V. B. Verma, A. E. Lita, M.R. Vissers, F. Marsili, D. P. Pappas, R. P. Mirin, and S. W. Nam, "Superconducting Nanowire Single Photon Detectors Fabricated from an Amorphous Mo0.75Ge0.25 Thin Film," *Appl. Phys. Lett.* 105, 022602, 2014.
40. E. A. Dauler, M. E. Grein, A. J. Kerman, F. Marsili, S. Miki, S. W. Nam, M. D. Shaw, H. Terai, V. B. Verma, and T. Yamashita, "Review of Superconducting Nanowire Single-Photon Detector System Design Options and Demonstrated Performance," *Opt. Eng.* 53, 081907, 2014.
41. V. B. Verma, R. Horansky, F. Marsili, J. A. Stern, M. D. Shaw, A. E. Lita, R. P. Mirin and S. W. Nam, "A Four-Pixel Single-Photon Pulse-Position Array Fabricated from WSi Superconducting Nanowire Single-Photon Detectors," *Appl. Phys. Lett.* 104, 051115, 2014.
42. J. W, Kooi, R. A Chamberlin, R. R. Monje, A. Kovacs, F. Rice, H. Yoshida, B. Force, K. Cooper, D. Miller, M. Gould, D. Lis, B. Bumble, R. LeDuc, J. A. Stern, and T.G.G. Phillips, "Performance of the Caltech Submillimeter Observatory Dual-Color 180-720 GHz Balanced SIS Receivers," *IEEE Trans. Terahertz Sci.* 4, 149, 2014.
43. P. Szypryt, G. E. Duggan, B. A. Mazin, S. R. Meeker, M. J. Strader, J. C. van Eyken, D. Marsden, K. O'Brien, A. B. Walter, G. Ulbricht, T. A. Prince, C. Stoughton, and B. Bumble, "Direct Detection of SDSS J0926+3624 Orbital Expansion with ARCONS," *Mon. Not. R. Astron. Soc.* 439, 2765, 2014.
44. J. Gao, M.R. Vissers, M. Sandberg, D. Li, H.M. Cho, C. Bockstiegel, B.A. MAzin, H. G. Leduc, S. Chaudhuri, D. P. Pappas, and K. D. Irwin, "Properties of TiN for Detector and Amplifier Applications," *J. Low Temp. Phys.* 176 (3–4), 136, 2014.
45. M. Faverzani, P. K. Day, P. Falferi, E. Ferri, A. Giachero, C. Giordano, H. G. LeDuc, B. Marghesin, R. Mezzena, R. Nizzolo, A. Nucciotti, "Development of Superconducting Microresonators for a Neutrino Mass Experiment," *J. Low Temp. Phys.* 176 (3–4), 530, 2014.

46. J. J. Bock, C. D. Dowell, S. R. Hildebrandt, H. T. Nguyen, R. O'Brient, Z. K. Staniszewski, A. D. Turner, et al., Bicep2 Collaboration, "Detection of B-Mode Polarization at Degree Angular Scales by BICEP2," *Phys. Rev. Lett.* 112, 241101, 2014.

47. J. J. Bock, P. K. Day, C. D. Dowell, S. R. Hildebrandt, N. Llombart, H. T. Nguyen, R. O'Brient, Z. K. Staniszewski, A. D. Turner, P. Wilson, et al., Bicep2 Collaboration, "Bicep2. II. Experiment and Three-Year Data Set," *Astrophys. J.* 792 (1) 62, 2014.

48. B. R. Johnson, P.A.R. Ade, D. Araujo, K. J. Bradford, D. Chapman, P. K. Day, J. Didier, S. Doyle, H. K.Eriksen, D. Flanigan, C. Groppi, S. Hillbrand, G. Jones, M. Limon, P. Mauskopf, H. McCarrick, A. Miller, T. Mroczkowski, B. Reichborn-Kjennerud, B. Smiley, J. Sobrin, I. K. Wehus, and J. Zmuidzinas, "The Detector System for the Stratospheric Kinetic Inductance Polarimeter (SKIP)," *J. Low Temp. Phys.* 176 (5–6), 741, 2014.

49. E. Shirokoff, P. S. Barry, C. M. Bradford, G. Chattopadhyay, P. Day, S. Doyle, S. Hailey-Dunsheath, M. I. Hollister, A. Kovacs, H. G. Leduc, C. M. McKenney, P. Mauskopf, H. T. Nguyen, R. O'Brient, S. Padin, T. J. Reck, L. J. Swenson, C. E. Tucker, and J. Zmuidzinas, "Design and Performance of SuperSpec: An On-Chip, KID-Based, mm-Wavelength Spectrometer," *J. Low Temp. Phys.* 176 (5–6), 657, 2014.

50. S. Hailey-Dunsheath, P. S. Barry, C. M. Bradford, G. Chattopadhyay, P. Day, S. Doyle, M. Hollister, A. Kovacs, H.G. LeDuc, N. Llombart, P. Mauskopf, C. McKenney, R. Monroe, H. T. Nguyen, R. O'Brient, S. Padin, T. Reck, E. Shirokoff, L. Swenson, C. E. Tucker, and J. Zmuidzinas, "Optical Measurements of SuperSpec: A Millimeter-Wave On-Chip Spectrometer," *J. Low Temp. Phys.* 176 (5–6), 841, 2014.

51. B. Cornell, D. C. Moore, S. R. Golwala, B. Bumble, P. K. Day, H. G. LeDuc, and J. Zmuidzinas, "Particle Detection Using MKID-Based Athermal-Phonon Mediated Detectors," *J. Low Temp. Phys.* 176 (5–6), 891, 2014.

52. H. McCarrick, D. Flanigan, G. Jones, B. R. Johnson, P. Ade, D. Araujo, K. Bradford, R. Cantor, G. Che, P. Day, S. Doyle, H. Leduc, M. Limon, V. Luu, P. Mauskopf, A. Miller, T. Mroczkowski, C. Tucker, and J. Zmuidzinas, "Horn-Coupled, Commercially-Fabricated Aluminum Lumped-Element Kinetic Inductance Detectors for Millimeter Wavelengths," *Rev. Sci. Instrum.* 85 (12), 123117, 2014.

53. V. B. Verma, R. Horansky, F. Marsili, J. A. Stern, M. D. Shaw, A. E. Lita, R. P. Mirin and S. W. Nam, "A Four-Pixel Single-Photon Pulse-Position Array Fabricated from WSi Superconducting Nanowire Single-Photon Detectors," *Appl. Phys. Lett.* 104, 051115, 2014.

54. C. Lee, Z. Zhang, G. R. Steinbrecher, H. Zhou, J. Mower, T. Zhong, L. Wang, X. Hu, R. D. Horansky, V. B. Verma, A. E. Lita, R. P. Mirin, F. Marsili, M. D. Shaw, S. Woo Nam, G. W. Wornell, F.N.C Wong, J. H. Shapiro, and D. Englund, "Entanglement-Based Quantum Communication Secured by Nonlocal Dispersion Cancellation," *Phys. Rev. A* 90, 062331, 2014.

55. R. Valivarthi, I. Lucio-Martinez, A. Rubenok, P. Chan, F. Marsili, V. B. Verma, M. D. Shaw, J. A. Stern, J. A Slater, D. Oblak, S. W. Nam, and W. Tittel, "Efficient Bell State Analyzer for Time-Bin Qubits with Fast-Recovery WSi Superconducting Single Photon Detectors," *Opt. Express* 22, 24497, 2014.

56. D. R. Hamel, L. K. Shalm, H. Hübel, A. J. Miller, F. Marsili, V. B. Verma, R. P. Mirin, S. W. Nam, K. J Resch, and T. Jennewein, "Direct Generation of Three-Photon Polarization Entanglement," *Nat. Photonics* 8, 801, 2014.

57. F. Bussières, C. Clausen, A. Tiranov, B. Korzh, V. B. Verma, S. W. Nam, F. Marsili, A. Ferrier, P. Goldner, H. Herrmann, C. Silberhorn, W. Sohler, M. Afzelius, and N. Gisin, "Quantum Teleportation from a Telecom-Wavelength Photon to a Solid-State Quantum Memory," *Nat. Photonics* 8, 775, 2014.

58. V. B. Verma, B. Korzh, F. Bussières, R. D. Horansky, A. E. Lita, F. Marsili, M. D. Shaw, H. Zbinden, R. P. Mirin, and S. W. Nam, "High-Efficiency WSi Superconducting Nanowire Single-Photon Detectors Operating at 2.5 K," *Appl. Phys. Lett.* 105, 122601, 2014.

59. V. B. Verma, A. E. Lita, M. R. Vissers, F. Marsili, D. P. Pappas, R. P. Mirin, and S. W. Nam, "Superconducting Nanowire Single Photon Detectors Fabricated from an Amorphous Mo0. 75Ge0. 25 thin film," *Appl. Phys. Lett.* 105, 022602, 2014.

60. E. Dauler, M. Grein, A. Kerman, F. Marsili, S. Miki, S. W. Nam, M. Shaw, H. Terai, V. Verma, and T. Yamashita, "Review of Superconducting Nanowire Single-Photon Detector System Design Options and Demonstrated Performance," *Opt. Eng.* 53, 081907, 2014.

61. C. R. Webster et al., "Mars Methane Detection and Variability at Gale Crater," *Science* 347, 415–17, 2015.

CONFERENCE AND PROCEEDINGS PUBLICATIONS

1. P. Goldsmith, I. Mehdi, J. Kawamura, J. V. Siles, C. Lee, G. Chattopadhyay, and J. A. Stern, "Next Generation Submillimeter Heterodyne Focal Plane Array Technology," *American Astronomical Society Meeting Abstracts (Vol. 223)*, Washington, D.C., Jan. 2014.

2. J. V. Siles, I. Mehdi, C. Lee, R. H. Lin, P. J. Bruneau, E. T. Schlecht, J. H. Kawamura, and P. F. Goldsmith, "A Multi-Pixel Room-Temperature Local Oscillator Sub-System for Array Receivers at 1.9 THz," *Proc. of SPIE Astronomical Telescopes and Instrumentation*, Montréal, Canada, June 2014.

3. M. Wolak, T. Tan, D. Cunnane, B. Karasik, and X. Xi, "Fabrication and Study of Ultrathin MgB2 Films for Hot Electron Bolometer Applications," *Bulletin of the American Physical Society, A47.00006,* APS March Meeting 2014 Volume 59, Number 1, Denver, CO, March 3–7, 2014.

4. Sergeev, B. Wen, R. Yakobov, S. Vitkalov, and B. Karasik, "Electron Heating in Superconducting Cuprate Heterostructures and Its Application for Advanced Sensing," *Bulletin of the American Physical Society, A47.00007,* Denver, CO, APS March Meeting 2014, Volume 59, Number 1, March 3–7, 2014.

5. J. V. Siles, C. Lee, R. Lin, G. Chattopadhyay, and I. Mehdi, "Progress Towards a Room-Temperature 4.7 THz Multiplied Local Oscillator Source to Enable Neutral Oxygen Observation," *Proc. of the 25th International Symposium on Space Terahertz Technology (ISSTT 2014)*, Moscow, Russia, Apr. 2014.

6. G. Chattopadhyay, T. Reck, C. Jung-Kubiak, C. Lee, J. Siles, N. Chahat, K. Cooper, E. Schlecht, M. Alonso-DelPino, and I. Mehdi, "Terahertz Antennas with Silicon Micromachined front-end," *8th European Conference on Antennas and Propagation (EuCAP),* The Hague, Netherlands, Apr. 2014.

7. I. Mehdi, J. V. Siles, R. Lin, C. Lee, P. J. Bruneau, E. Schlecht, J. Kawamura, and P. Goldsmith, "4-Pixel Frequency Multiplied Source For High-Resolution Heterodyne Array Receivers at 1.9 THz," *Proc. of the 25th International Symposium on Space Terahertz Technology (ISSTT 2014)*, Moscow, Russia, Apr. 2014.

8. D. Cunnane, J. H. Kawamura, B. S. Karasik, M. A. Wolak and X. X.Xi, "Temperature Dependent Parameters of MgB2 Hot Electron Bolometer Mixers," *Proc. of 2014 Applied Superconductivity Conference,* Charlotte, N.C., Aug. 2014.

9. D. Cunnane, J. H. Kawamura, B. S. Karasik, M. A. Wolak and X. X. Xi, "MgB2 Hot Electron Bolometers Operating Above 20 K," *Proc. of the 25th International Symposium on Space Terahertz Technology,* Moscow, Russia, April 2014.

10. B. S. Karasik, "Normal Metal HEB Detector with Johnson Noise Thermometry Readout," *Proc. of the 25th International Symposium on Space Terahertz Technology,* Moscow, Russia, April 2014.

11. B. S. Karasik, "Superconducting and Graphene Bolometers for Emerging High-Sensitivity THz Applications in Space," *The 3nd Russia-Japan-USA Symposium: The Fundamental & Applied Problems of Terahertz Devices & Technologies* (RJUS TeraTech-2014), June 17–21, Buffalo, NY, pp. 13–14. 2014.

12. K. B. Cooper and R. J. Dengler, "Residual Phase Noise and Transmit/Receive Isolation in a Submillimeter-Wave FMCW Radar," *IEEE/MTT-S International Microwave Symposium*, 0900-0920, Tampa Bay, FL, June 2014.

13. J. V. Siles, "Terahertz Device and Circuits for High-Resolution array cameras and transceivers for astrophysics, Planetary Science and Radar Imaging Applications," *Proc. of the 2014 IEEE Lester Eastman Conference on High Performance Devices,* Ithaca, NY, Aug. 2014.

14. C. Jung-Kubiak, T. Reck, and G. Chattopadhyay, "Integrated Calibration Switches for Compact Planetary Instruments," *39th Int. Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz,* Tucson, AZ, Sep. 2014.

15. T. Reck, C. Jung-Kubiak, C. Leal-Sevillano, and G. Chattopadhyay, "Silicon Micromachined Components at 0.75 to 1.1 THz," *39th Int. Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz,* Tucson, AZ, Sep. 2014.

16. N. Llombart, M. Alonso-DelPino, C. Lee, G. Chattopadhyay, C. Jung-Kubiak, and I. Mehdi, "On the Development of Silicon Micromachined Lens Antennas for THz Integrated Heterodyne Arrays," *39th Int. Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz,* Tucson, AZ, Sep. 2014.

17. C. Lee, G. Chattopadhyay, M. Alonso-delPino, and N. Llombart, "6.4 mm Diameter Silicon Micromachined Lens for THz Dielectric Antenna," *39th Int. Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz,* Tucson, AZ, Sep. 2014.

18. V. Siles, "Ultra-Compact Integration Techniques for Millimeter and Submillimeter-Wave Sources and Transceivers Using Multi-Layer Silicon Micromachining and On-Chip Power-Combining Techniques," invited presentation at Recent Progresses in Millimetre-Wave Monolithic and Multilayer Integrated Circuits and Module Integration Techniques Workshop, *2014 IEEE International Microwave & RF Conference (IMaRC)*, Bangalore, India, Sep. 2014.

19. N. Gautam, J. Kawamura, N. Chahant, B. Karasik, P. Focardi, S. Gulkis, L. Pfeiffer, and M. Sherwin, "Tunable Antenna Coupled Intersubband Terahertz Detector," *Proc. of the 39th Int. Conf. on IR, MM, and THz Waves,* pp. 1–2, Tucson, AZ, Sept. 14–19.

20. V. Siles, C. Lee, R. Lin, G. Chattopadhyay, and I. Mehdi, "Capability of Room-Temperature Solid State Coherent Sources in the THz Range," invited keynote talk, *Proc. of the 34th International Conference on Infrared, Millimeter, and Terahertz Waves*, Tucson, AZ, Sep. 2014.

21. G. Chattopadhyay, T. Reck, A. Tang, C. Jung-Kubiak, C. Lee, J. V. Siles, E. Schlecht, M-C. F. Chang, and I. Mehdi, "Silicon Micromachined High-Resolution Terahertz Spectroscopic Instrument for Planetary Missions," *Proc. of International Workshop on Instrumentation for Planetary Missions,* Greenbelt, MD, Nov. 2014.

22. N. Gautam, M. Sherwin, J. Kawamura, B. Karasik, P. Focardi, S. Gulkis, and L. Pfeiffer, "A Heterodyne Detector for Terahertz Spectroscopy of Planets and Comets," *The 2nd Int. Workshop on Instrumentation for Planetary Missions (IPM2014),* Greenbelt, MD, Nov. 4–7, 2014.

23. B. S. Karasik, C. B. McKitterick, and D. E. Prober, "Monolayer Graphene Bolometer as a Sensitive Far-IR Detector," *Proc. SPIE,* Vol. 9153, 915309, 2014.

24. D. Cunnane, J. Kawamura, B. S. Karasik, M. A. Wolak, and X. X.Xi, "Development of the Hot-Electron THz Bolometric Mixer Using MgB2 Thin Film," *Proc. SPIE,* Vol. 9153, 91531Q, 2014.

25. B. S. Karasik, C. B. McKitterick, and D. E. Prober, "Monolayer Graphene Bolometer as Sensitive Far-IR Detector," *Proc. of the SPIE Astronomical Telescopes + Instrumentation 2014 Symposium*, Quebec, Canada, July 2014.

26. D. P. Cunnane, M. A. Wolak, T. Tan, J. H. Kawamura, X. X. Xi, and B. S. Karasik, "Development of the Hot-Electron THz Bolometric Mixer Using Thin MgB2 Film," *Proc. of the SPIE Astronomical Telescopes + Instrumentation 2014 Symposium*, Quebec, Canada, July 2014.

27. T. Chui, A. Kleinsasser, B. Karasik, B. Bumble, T. Lanting, and E. Ladizinsky, "SQUID Noise Measurements for Fabrication Process Investigations," *Proc. of 2014 Applied Superconductivity Conference*, Charlotte, NC, Aug. 2014.

28. N. Rouhi, C. Jung-Kubiak, V. White, M. Dickie, S. Forouhar, and C. Marrese-Reading, "High Aspect Ratio Three Dimensional Silicon Micro-Needles Using Photoresist Re-Flow and One-Step-Etch Process," *MRS Fall Meeting*, Boston, MA, Dec. 2014.

29. E. Hoenk, S. Nikzad, A. G. Carver, T. J. Jones, J. Hennessy, A. D. Jewell, J. Sgro, S. Tsur, M. McClish, and R. Farrell, "Superlattice-Doped Silicon Detectors: Progress and Prospects," *Proc. SPIE 9154, High Energy, Optical and Infrared Detectors for Astronomy VI*, edited by A. D. Holland and J. Beletic, 2014 915413.

30. E. T. Hamden, A. D. Jewell, S. Gordon, J. Hennessy, M. Hoenk, S. Nikzad, D. Schiminovich, and D. C. Martin, "High Efficiency CCD Detectors at UV Wavelengths," *Proc. SPIE 9144, Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray*, edited by T. Takahashi, J.-W. A. den Herder, and M. Bautz, 2014 91442X.

31. D. Jewell, J. Hennessy, E. Hamden, T. Goodsall, C. Shapiro, A. Carver, T. J. Jones, M. E. Hoenk, and S. Nikzad, "Using ALD to Enable High Performance Detectors and Optics for Astronomy and Planetary Exploration," *12th International Baltic Conference on Atomic Layer Deposition*, Helsinki, Finland, 2014.

32. J. Hennessy, L. D. Bell, S. Nikzad, P. Suvarna, J. M. Leathersich, J. Marini, and F. (Shadi) Shahedipour-Sandvik, "Atomic-Layer Deposition for Improved Performance of III-N Avalanche Photodiodes," *MRS Proceedings*, v1635, 2014.

33. J. Hennessy, L. D. Bell, S. Nikzad, P. Suvarna, J. Bulmer, J. M. Leathersich, J. Marini and F. Shahedipour-Sandvik, "ALD Surface Passivation of GaN for Improved Photodiode Performance," *56th Electronic Materials Conference*, Santa Barbara, CA, 2014.

34. P. Suvarna, J. Bulmer, J. M. Leathersich, J. Marini, F. Shahedipour-Sandvik, L. D. Bell, J. Hennessy and S. Nikzad, "Advanced Micropixel Design for Separate Absorption and Multiplication III-N Avalanche Photodiodes," *56th Electronic Materials Conference*, Santa Barbara, CA, 2014.

35. J. Hennessy, A. Jewell, S. Nikzad, B. Balasubramanian, C. Moore, and K. France, "ALD Metal Fluorides for Optical Coatings in the Ultraviolet," *14th International Conference on Atomic Layer Deposition*, Kyoto, Japan, 2014.

36. S. Nikzad, M. E. Hoenk, J. J. Hennessy, A. D. Jewell, A. G. Carver, T. J. Jones, S. L. Cheng, T. Goodsall, and C. Shapiro, "High-Performance Silicon Imaging Arrays for Cosmology, Planetary Sciences, and other Applications," invited paper, *2014 International Electron Devices Meeting*, San Francisco, CA, 2014.

37. S. Nikzad, "High Performance Silicon Imagers and Their Applications," *High Performance Silicon Imaging,* editor, D. Durinig, Woodhead Publishing, Elsevier, 2014.

38. D. Z. Ting, C. J. Hill, A. Soibel, S. A. Keo, J. M. Mumolo, and S. D. Ganapala, "Midwave Barrier Infrared Detector with Quantum Dot Enhancement," *Proc. of the IEEE Summer Topical Meeting Series*: July 14–16, Montréal, Québec, Canada, 2014.

39. D. Z. Ting, et al., "Theoretical Aspects of Minority Carrier Extraction in Unipolar Barrier Infrared Detectors," in *Proc. of the 2014 U.S. Workshop on the Physics and Chemistry of II-VI Materials*, October 21–23, Baltimore, MD, 2014.

40. L. Höglund, D. Z. Ting, A. Khoshakhlagh, A. Soibel, C. J. Hill, A. Fisher, S. Keo, and S. D. Gunapala, "Minority Carrier Lifetime Studies of Narrow Bandgap Antimonide Superlattices," *Proc. of SPIE, 8993,* 89930Y, 2014.

41. S. D. Gunapala, D. Z. Ting, A. Soibel, A. Khoshakhlagh, S. A. Keo, C. J. Hill, S. B. Rafol, L. Baker, J. K. Liu, J. M. Mumolo, A. Fisher, R. Kowalczyk, and R. Rosenberg, P. R. Pinsukanjana, E. D. Fraser, K. P. Clark, K. Roodenko, J. M. Fastenau, D. Loubychev, Y. M. Qiu, A. W. K. Liu, R. Bornfreund, N. Jolivet, and J. L. Miller, "Development of Ga-free InAs/InAsSb LWIR Detector and Focal Plane for Army Degraded Visual Environment Application," *Proc. of the Military Sensing Symposia (MSS)*, Gaithersburg, MD, September 8–12, 2014.

42. P.-K. Liao, D. Lan, G. Yang, K. P. Clark, E. D. Fraser, K. Roodenko, P. R. Pinsukanjana, and Y.-C. Kao, D. Z. Ting, C. J. Hill, A. Soibel, L. Höglund, and S. D. Gunapala, "Recent Development of Domestic Large Diameter GaSb Substrates at IntelliEPI," *Proc. of the Military Sensing Symposia (MSS)*, Gaithersburg, MD, September 8–12, 2014.

43. S. D. Gunapala, S. B. Rafol, D. Z. Ting, Soibel, L. Höglund, C. J. Hill, A. Khoshakhlagh, J. K. Liu, J. M. Mumolo, and S. A. Keo, "1/f Noise QWIP Infrared Focal Plane Arrays," *IEEE Photonics Conference 2014 Digest,* La Jolla, CA, October 12–16, 2014.

44. S. D. Gunapala, D. Z. Ting, A. Soibel, S. A. Keo, S. B. Rafol, J. M. Mumolo, J. K. Liu, C. J. Hill, A. Khoshakhlagh, L. Höglund, and E. M. Luong, "Development of Quantum Well, Quantum Dot, and Antimonide Superlattice Infrared Photodetectors," *Optical Society of America: Latin America Optics & Photonics Conference Digest,* Cancun, Mexico, November 16–21, 2014.

45. V. J. Scott and X. Amashukeli, "An RF-Powered Micro-Extractor for Efficient Extraction and Hydrolysis," *AGU Conference*, San Francisco, CA, December 2014.

46. V. J. Scott, R. Toda, R. Murthy, L. Del Castillo, and H. Manohara, "CNT Field Emitters: Growth and In Situ Welding on Metal Surfaces," *ACS Conference,* San Francisco, CA, August 2014.

47. V. J. Scott and X. Amashukeli, "An RF-Powered Micro-Reactor for Efficient Extraction and Hydrolysis," *ACS Conference,* San Francisco, CA, August 2014.

48. P. Backes, C. McQuin, M. Badescu, A. Ganino, H. Manohara, Y. Bae, R. Toda, N. Wiltsie, S. Moreland, J.Grimes-York, P. Walkemeyer, E. Kulczycki, C. Dandino, R. Smith, M. Williamson, D. Wai, R. Bonitz, A. San Martin, and B. Wilcox, "Sampling System Concepts for a Touch-and-Go Architecture Comet Surface Sample Return Mission," *AIAA Space 2014, Conference and Exposition,* San Diego, CA, August 4–7, 2014. DOI:10.2514/6.2014-4379.

49. R. M. Briggs, C. Frez, C. E. Borgentun, M. Bagheri, S. Forouhar, and R. D. May, "Five-Channel Infrared Laser Absorption Spectrometer for Combustion Product Monitoring Aboard Manned Spacecraft," *44th International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics (AIAA),* Tucson, AZ, 2014.

50. P. A. Willis, M. L. Cable, M. F. Mora, A. M. Stockton, K. P. Hand, S.M. Hörst, M.A. Tolbert, C. He, and M.A. Smith, "Non-Aqueous Microchip Capillary Electrophoresis of Long-Chain Aliphatic Amines in Titan Simulant Material and Fatty Acids in Deep Ocean Sediments," *The Eighteenth International Conference on Miniaturized Systems for Chemistry and Life Sciences (μTAS 2014)*, San Antonio, TX, October 2014.

51. M. Stockton, J. Kim, P.A.Willis, R. Lillis, R. Amundson, et al., "Microfluidic Life Analyzer (MILA)," *International Workshop on Instrumentation for Planetary Missions*, Greenbelt, MD, #1045, November 2014.

52. F. Marsili, V. B. Verma, M. J. Stevens, J. A. Stern, M. D. Shaw, A. J. Miller, D. Schwarzer, A. Wodtke, R. P. Mirin, and S. W. Nam, "Mid-Infrared Superconducting Nanowire Single-Photon Detectors Based on WSi," *Applied Superconductivity Conference*, Charlotte, NC, August 2014.

53. F. Marsili, M. J. Stevens, A. Kozorezov, V. B. Verma, C. Lambert, J. A. Stern, R. Horansky, S. Dyer, M. D. Shaw, R. P. Mirin, and S. W. Nam, "Hotspot Relaxation Time in Current Carrying WSi Superconducting Nanowires," *Applied Superconductivity Conference,* Charlotte, NC, August 2014.

54. A.Kozorezov, C. Lambert, F. Marsili, M. J. Stevens, V. B. Verma, R. Horansky, S. Dyer, M. D. Shaw, J. A. Stern, R. P. Mirin, and S. W. Nam, "Quasi-particle Recombination in the Relaxing Hot Spot in Current-Carrying Superconducting Nanowires," *Applied Superconductivity Conference,* Charlotte, NC, August 2014.

55. D. Beyer, M. D. Shaw, F. Marsili, A. E. Lita, V. B. Verma, G. V. Resta, J. A. Stern, P. Ravindran, S. Chang, J. Bardin, D. S. Russel, J. W. Gin, F. D. Patawaran, R. P. Mirin, S. W. Nam, and W. H. Farr, "Tungsten Silicide Superconducting Nanowire Single-Photon Detectors Fabricated Using Optical Lithography," *Applied Superconductivity Conference*, Charlotte, NC, August 2014.

56. F. Marsili, M. D. Shaw, G. V. Resta, J. A. Stern, A. D. Beyer, P. Ravindran, S. Chang, J. Bardin, D. S. Russel, J. W. Gin, F. D. Patawaran, V. B. Verma, R. P. Mirin, S. W. Nam, and W. H. Farr, "Arrays of WSi Superconducting Nanowire Single Photon Detectors" *Applied Superconductivity Conference*, Charlotte, NC, August 2014.

57. V. B. Verma, A.E. Lita, M. R. Vissers, F. Marsili, D. P. Pappas, R. P. Mirin, and S. W. Nam, "High-Efficiency Superconducting Nanowire Single Photon Detectors Based on Amorphous Mo0.75Ge0.25," *Conference on Lasers and Electro-Optics (CLEO)* San Jose, CA, June 2014.

58. C. Lee, Z. Zhang, J. C. Mower; G. Steinbrecher, H. Zhou, L. Wang, R. Horansky, V. B. Verma, M. Allman, A. E. Lita, R. P. Mirin, F. Marsili, A. D. Beyer, M. D. Shaw, S. W. Nam. G. W. Wornell, F. N. C. Wong, J. H. Shapiro, and D. Englund, "High-Dimensional Time-Energy Entanglement-Based Quantum Key Distribution Using Dispersive Optics," *Conference on Lasers and Electro-Optics (CLEO)* San Jose, CA, June 2014.

59. F. Marsili, M. J. Stevens, A. Kozorezov, V. B. Verma, C. Lambert, J. A. Stern, R. Horansky, S. D. Dyer, M. D. Shaw, R. P. Mirin, and S. W. Nam, "Hotspot Dynamics in Current Carrying WSi Superconducting Nanowires," *Conference on Lasers and Electro-Optics (CLEO),* San Jose, CA, June 2014.

60. D. Shaw, K. Birnbaum, M. Cheng, M. Srinivasan, K. Quirk, J. Kovalik, A. Biswas, A. D. Beyer, F. Marsili, V. Verma, R. P. Mirin, S. W. Nam, J. A. Stern, and W. H. Farr, "A Receiver for the Lunar Laser Communication Demonstration Using the Optical Communications Telescope Laboratory," *Conference on Lasers and Electro-Optics (CLEO),* San Jose, CA, June 2014.

61. F. Bussières, C. Clausen, A. Tiranov, B. Korzh, V. B. Verma, S. W. Nam, F. Marsili, A. Ferrier, P. Goldner, H. Herrmann, C. Silberhorn, W. Sohler, M. Afzelius, and N. Gisin, "Quantum Teleportation from a Telecom-Wavelength Photon to a Solid-State Quantum Memory," *Conference on Lasers and Electro-Optics (CLEO),* San Jose, CA, June 2014.

62. V. Verma, M. S. Allman, R. Horansky, F. Marsili, J. A. Stern, A. D. Beyer, M. D. Shaw, S. W. Nam, and R. P. Mirin, "Progress and Prospects for High Efficiency and Gigacount per Second Detectors for Quantum Repeaters Using Superconducting Nanowire Detectors," *Conference on Lasers and Electro-Optics (CLEO),* San Jose, CA, June 2014.

63. T. Gerrits, F. Marsili, M. D. Shaw, T. J. Bartley, and S. W. Nam, "Four-Photon Joint Spectral Probability Distribution of a High Spectral-Purity Photon Source," *Conference on Lasers and Electro-Optics (CLEO),* San Jose, CA, June 2014.

64. S. W. Nam, V. Verma, M. Allman, R. Horansky, R. P. Mirin, A. Lita, F. Marsili, M. Shaw, A. D. Beyer, and J. A. Stern, "Nanowire Superconducting Single Photon Detectors Progress and Promise," *Conference on Lasers and Electro-Optics (CLEO),* San Jose, CA, June 2014.

65. M. Allman, V. B. Verma, R. Horansky, F. Marsili, J. A. Stern, M. D. Shaw, A. D. Beyer, R. P. Mirin, and Sae Woo Nam, "Progress Towards a Near IR Single-Photon Superconducting Nanowire Camera for Free-Space Imaging of Light," *Conference on Lasers and Electro-Optics (CLEO),* San Jose, CA, June 2014.

66. M. D. Shaw, F. Marsili, A. D. Beyer, W. H. Farr, G. Resta, V. B. Verma, R. D. Horansky, A. Lita, R. P. Mirin, and S. W. Nam, "Tungsten Silicide Superconducting Nanowire Single Photon Detector Arrays for Deep Space Optical Communication," *SPIE Defense Security and Sensing (SPIE DSS 2014),* Baltimore, MD, April 2014.

67. J. C. Bardin, P. Ravindran, S. Chang, C. Mohamed, M. D. Shaw, F. Marsili, G. Resta, and W. H. Farr, "Cryogenic SiGe Integrated Circuits for Superconducting Nanowire Single Photon Detector Readout," *SPIE Defense Security and Sensing 2014 (SPIE DSS 2014)*, Baltimore, MD, April 2014.

68. T. Gerrits, F. Marsili, M. D. Shaw, T. J. Bartley, and S. W.Nam, “Four-Photon Joint Spectral Probability Distribution of a High Spectral-Purity Photon Source,” *CLEO: Applications and Technology,* San Jose, CA, 2014.

69. M. Allman, V. B Verma, R. Horansky, F. Marsili, J. A Stern, M. D. Shaw, A. D. Beyer, R. P. Mirin, and S. W. Nam, “Progress Towards a Near IR Single-Photon Superconducting Nanowire Camera for Free-Space Imaging of Light,” *CLEO: Applications and Technology*, San Jose, CA, 2014.

70. V. B. Verma, F. Marsili, J. A. Stern, A. Beyer, M. D. Shaw, S. Nam, and R. P. Mirin, “Progress and Prospects for High Efficiency and Gigacount per Second Detectors for Quantum Repeaters Using Superconducting Nanowire Detectors,” *CLEO Lasers and Electro Optics,* San Jose, CA, 2014.

71. F. Marsili, M. J. Stevens, A. Kozorezov, V. B. Verma, C. Lambert, J. A. Stern, R. Horansky, S. Dyer, M. D. Shaw, R. P. Mirin, and S. W. Nam, “Hotspot Dynamics in Current Carrying WSi Superconducting Nanowires,” *CLEO Lasers and Electro Optics*, San Jose, CA, 2014.

72. M. D. Shaw, K. Birnbaum, M. Cheng, M. Srinivasan, K. Quirk, J. Kovalik, A. Biswas, A. Beyer, F. Marsili, V. B. Verma, R. P. Mirin, S.W. Nam, J. A. Stern and W. H. Farr, “A Receiver for the Lunar Laser Communication Demonstration Using the Optical Communications Telescope Laboratory,” *CLEO: Science and Innovations*, San Jose, CA, 2014.

73. A. C. Weber, A. D.Turner, K. Megerian, et al., “Keck Array and BICEP3: Spectral Characterization of 5000+ Detectors,” *Proc. SPIE Vol. 9153*, August 19, 2014.

74. A. C. Weber, A. D.Turner, K. Megerian, et al., ”Pre-Flight Integration and Characterization of the SPIDER Balloon-Borne Telescope,” *Proc. SPIE Volume 9153*, August 19, 2014.

75. A. C. Weber, A. D.Turner, K. Megerian, et al., “Attitude Determination for Balloon-Borne Experiments,” *Proc. SPIE Vol. 9145*, September 2014.

76. A. C. Weber, A. D.Turner, K. Megerian, et al., “BLAST Bus Electronics: General-Purpose Readout and Control for Balloon-Borne Experiments,” *Proc. SPIE Vol. 9145*, September 2014.

77. A. C. Weber, A. D.Turner, K. Megerian, et al., “Design and Construction of a Carbon Fiber Gondola for the SPIDER Balloon-Borne Telescope,” *Proc. SPIE Vol. 9145*, September 2014.

78. A. C. Weber, A.D.Turner, K. Megerian, et al., “Pointing Control for the SPIDER Balloon-Borne Telescope,” *Proc. SPIE Vol. 9145*, September 2014.

79. A. Biswas, J. M. Kovalik, M. W. Wright, W. T. Roberts, M. K. Cheng, K. J. Quirk, M. Srinivasan, M. D. Shaw, and K. M. Birnbaum, “LLCD Operations Using the Optical Communications Telescope Laboratory (OCTL),” Proc. *SPIE 8971, Free-Space Laser Communication and Atmospheric Propagation XXVI, 89710X*, San Francisco, CA, 2014.

80. T. Zhong, H. Zhou, L. Wang, G. Wornell, Z. Zhang, J. H. Shapiro, F. Wong, R. Horansky, V. Verma, A. Lita, R. P Mirin, T. Gerrits, S. W. Nam, A. Restelli, J. C. Bienfang, F. Marsili, and M. D Shaw, “Photon-Efficient High-Dimensional Quantum Key Distribution,” *CLEO: Applications and Technology*, San Jose, CA, 2014.

81. T. Zhong, C. Lee, Z. Zhang, H. Zhou, G. Steinbrecher, J. Mower, L. Wang, R. D. Horansky, V. B. Verma, A. E. Lita, R. P. Mirin, T. Gerrits, A. Restelli, J. C. Bienfang, F. Marsili, M. D. Shaw, S. W. Nam, G.W. Wornell, D. Englund, J. H. Shapiro, and F.N.C. Wong, “Entanglement-based High-Dimensional Quantum Key Distribution,” *QCrypt,* Paris, France, 2014.

BOOK CONTRIBUTIONS

1. C. Lee, “Plasma-Processed Biomimetic Nano- and Micro-Structures” in *Biomimetic Architectures by Plasma Processing*, edited by Surojit Chattopadhyay. Pan Stanford Publishing Pte. Ltd. ISBN: 978-981-4463-94-2, 91–109, 2014.

2. S. Nikzad, A. D. Jewell, A. G. Carver, M/ E. Hoenk, J. N. Maki and L. D. Bell, “Digital Imaging for Planetary Exploration” in the *Handbook of Digital Imaging*, edited by M. Kriss, John Wiley & Sons, Ltd: Chichester, UK, 1531–1558, 2015.

3. F. A. Miranda and H. M. Manohara, “Nanotechnology for Nanoelectronic Devices,” in *Advanced Nanomaterials for Aerospace Applications*, ed. C. Cabrera, 2014-06-30, DOI: 10.4032/9789814463195.

NEW TECHNOLOGY REPORTS

1. J. Siles, C. Lee, G. Chattopadhyay, K. Cooper, I. Mehdi, R. Lin, and A. Peralta, “Ultra-High Power W-band/F-band Schottky Diode Based Frequency Multipliers,” NTR-49351.

2. Cecile Kubiak-Jung et al., “Silicon Micro-Emitters for Microfluidic Electrospray Propulsion Systems,” NTR-49549.

3. A. Khoshakhlagh, D. Z. Ting, and S. D. Gunapala, “P-compensated InAs/InAsSb Barrier Infrared Detectors,” March 10, 2014, NTR-49493.

4. D. Z. Ting, D. W. Wilson, S. A. Keo, A. Soibel, L.Höglund, and S. Gunapala, “Optical Enhancement for Spectral Imaging Infrared Focal Plane Arrays,” June 6, 2014, NTR-49556.

5. D. Z. Ting, A. Soibel, L.Höglund, and S. Gunapala, “Unipolar Barrier Dual-Band Infrared Detectors,” January 30, 2015, NTR-49789.

6. J. L. Hall, S. Sherrit, H. Manohara, M. Mojarradi, E. D. Archer, A. R. Sirota, and E. J. Brandon, “Wireless Surface Controlled and Pre-Programmable Inflow Control Valve/ Monitoring System,” NTR 49771, 2014.

7. J. L. Hall, S. Sherrit, H. Manohara, M. Mojarradi, E. J. Brandon, E. D Archer, A. R. Sirota, M. S. Garrett, E. A. Kulczycki, and R. C. Ewell, “Smart Pipe System for Oil Well Completions,” NTR 49729, 2014.

8. S. Sherrit, M. Badescu, H. Manohara, and S. Y. Bae, “Monolithic Actuated Endoscope (MAE),” NTR 49706, 2014.

9. C. Mcquin, M. Badescu, P. G. Backes, N. Wiltsie, S. J. Moreland, J. A. Grimes-York, H. Manohara, S. Y. Bae, and R. Toda, “BiBlade Sampling Chain,” NTR 94553, 2014.

10. V. Scott and X. Amashukeli, “Small Volume Pressurized Sample Handling System,” NTR 49601, 2014.

11. V. Scott and X. Amashukeli, “A Continuous-Flow Microfluidic Microwave-Assisted Chemical Reactor,” NTR 49602, 2014.

12. V. Scott, “Thin Layer Chromatography – Surface Enhanced Raman Spectroscopy,” NTR 49668, 2014.

13. H. Manohara, S. Y. Bae, L.Y. Del Castillo, and K. B. Chin, “Integrated In Situ Sensors for Harsh Environment Applications,” NTR 49068, 2013.

14. R. M. Briggs, C. Frez, C. E. Borgentun, M. Bagheri, S. Forouhar, and R. D. May, “Multi-Channel Laser Absorption Spectrometer for Combustion Product Monitoring,” NTR-49505, 2014.

15. R. M. Briggs, C. Frez, and S. Forouhar, “Low-Power-Consumption Single-Mode Quantum Cascade Lasers Fabricated Without Epitaxial Regrowth,” NTR-49512, 2014.

16. C. Frez, C. E. Borgentun, R. M. Briggs, M. Bagheri, and S. Forouhar, “Fabrication of Single-Mode, Distributed Feedback Interband Cascade Lasers Using Second-Order Lateral Bragg Gratings,” NTR-49559, 2014.

17. M. D. Shaw, et al., “Waveguide-Integrated Superconducting Nanowire Single Photon Detectors,” NTR-49701, 2014.

18. M.D. Shaw, et al., “A Free-Space Coupled Multi-Element Detector for Deep Space Optical Communication,” NTR-49463, 2014.

19. M.D. Shaw, et al., “Multimode Fiber-Coupled Tungsten Silicide Superconducting Nanowire Single Photon Detector Array,” NTR-49420, 2014.

PATENTS

1. C. Jung-Kubiak, T. Reck, B. Thomas, R. H. Lin, A. Peralta, J. J. Gill, C.Lee, J.V. Siles, R. Toda, G. Chattopadhyay, K. B. Cooper, and I. Mehdi, “Silicon Alignment Pins: An Easy Way To Realize A Wafer-To-Wafer Alignment,” U.S. Patent Serial No. 13/871,830 for May 2014.

2. G. Chattopadhyay, I. Mehdi, C. Lee, J. J. Gill, C. Jung-Kubiak, and N. Llombart, “Microfabrication Technique of Silicon Microlens Array for Terahertz Applications,” U.S. Patent Serial No. 13/869, 292 May 2014.

3. C. Jung-Kubiak, T. Reck, G. Chattopadhyay, J. V. Siles Perez, R. H. Lin, I. Mehdi, C. Lee, K. B. Cooper, and A. Peralta, “Multi-Step Deep Reactive Ion Etching Fabrication Process for Silicon-Based Terahertz Components,” Provisional Patent Serial No 61/812,097, April 2014.

4. D. Z. Ting, C. J. Hill, A. Soibel, S. V. Bandara, and S. D. Gunapala, “High Operating Temperature Barrier Infrared Detector with Tailorable Cutoff Wavelength,” U.S. Patent No. 8,928,036 B2, January 6, 2015.

5. David Z. Ting, Sarath D. Gunapala, Alexander Soibel, Jean Nguyen, and Arezou Khoshakhlagh, “Single-Band and Dual-Band Infrared Detector,” U.S. Patent No. 8,928,029 B2, January 6, 2015.

6. R. Toda, M. J. Bronikowski, E. M. Luong, and H. Manohara, “Method for Manufacturing a Carbon Nanotube Field Emission Device with Overhanging Gate,” U.S. Patent No. 8,916,394, Issue Date: 12/23/2014.

7. H. Manohara and M. Mojarradi, “Microscale Digital Vacuum Electronic Gates,” U.S. Patent No. 8,796,932, Issue Date: 08/05/2014.

8. C. Frez, C. Borgentun, R. M. Briggs, M. Bagheri, and S. Forouhar, “Fabrication of Single-Mode, Distributed Feedback Interband Cascade Lasers using Second-Order Lateral Bragg Gratings,” NPO-49559.

9. P. M. Echternach, C. M. Bradford, P. K. Day, K. J. Stone, and B. J. Pepper, “Capacitively Coupled Quantum Capacitance Detector,” NTR # 49779.

10. H. F. Greer, A. M. Fisher, P.A. Willis, H. Jiao, A. M. Stockton, M. F. Mora, and M. L. Cable, “Chemical Laptop,” U.S. Patent serial No. 62/134,946 for March 2015.

SPECIAL RECOGNITION

NASA AWARDS

1. Jeffrey Stern (posthumous) – **Exceptional Service Medal**: For pioneering development of mixers for the Heterodyne Instrument for the Far-Infrared on Herschel, THz mixers and WSi Superconducting Nanowire Single Photon Detectors, 2014.

2. David Z. Ting – **Exceptional Technology Achievement Medal**: Advanced Infrared Detector Technology, 2014.

3. Siamak Forouhar – **Exceptional Technology Achievement Medal**: Semiconductor Lasers, 2014.

4. Sarath D. Gunapala – **Outstanding Leadership Medal**: Outstanding Technical Management and Leadership in the development of novel infrared detectors which enable new NASA and defense applications, 2014.

5. James R. Wishard – **Exceptional Service Medal**: For exceptional service enabling advanced systems in JPL's Microdevices Laboratory to produce state-of-the-art technology and flight components for NASA science instruments, 2014.

6. E. Schlecht, J. V. Siles, C. Lee, R. H. Lin, B. Thomas, G. Chattopadhyay, and I. Mehdi – **Group Achievement Award**: Outstanding innovation and expertise in demonstrating super-compact multi-pixel receiver systems for submillimeter-wave atmospheric sounding of planetary atmospheres, 2014.

7. S. Cheng, T. Goodsall, E. Hamden. J. Hennessy, M. Hoenk, A. Jewell, T. Jones, and S.Nikzad – **Group Achievement Award**: For exceptional achievement in developing high performance scientific ultraviolet imagers, enabling new instruments for future planetary and astrophysics missions, 2014.

8. S. Forouhar, C. Frez, R. Briggs, M. Bagheri, and C. Borgentun – **Group Achievement Award**: Collaboration between JPL Semiconductor Laser Team and Harvard University, 2014.

9. A. Turner, et al. – **Group Achievement Award**: Outstanding Leadership and Successful Development of Advanced Superconducting Assemblies Enabling for Cosmic Microwave Background Observation Instruments, 2014.
10. R. Briggs, C. Frez, and S. Forouhar – **Group Achievement Award**: Development of single-mode quantum cascade lasers with ultra-low power consumption for infrared tunable laser spectrometers, 2014.

JPL AWARDS

1. F. Marsili, et al. – **Bonus Award**: Successful optical comm link with WSi detectors for Lunar Laser Optical Telescope (LLOT) ground station link to the LADEE spacecraft, 2014.
2. M. Runyan, et al. – **Group Achievement Award**: For outstanding contributions to the Euclid PDR Team, August 2014.
3. M. Runyan, A. Beyer, K. M. Birnbaum, M. K. Cheng, C. Esproles, V. Garkanian, J. M. Kovalik, M. D. Shaw, M. Srinivasan, W. B. Williamson, M. W. Wright, W. Farr, and A. Biswas. – **Group Achievement Award**: For the development of the LADEE Lunar Lasercom OCTL Terminal and its successful demonstration of multiple 78 and 39 Mbps optical downlink passes from the Moon, September 2014.
4. M. Shaw, F. Marsili, A. Beyer, and J. Stern – **Group Achievement Award**: For outstanding development and application of the revolutionary Tungsten Silicide superconducting nanowire detectors to optical communication and quantum science, September 2014.
5. M. Shaw, J. Stern, A. Beyer, and M. Runyan – **Group Achievement Award**: For the development of the LADEE Lunar Lasercom OCTL Terminal and its successful demonstration of multiple 78 and 39 Mbps optical downlink passes from the Moon, September 2014.
6. A. Turner, A. Weber, and K. Megerian – **Group Achievement Award**: Bicep 2 Focal Plane Team—The Team delivered 2 full focal planes of 95 GHz bolometers to the Keck project on an aggressive schedule and mitigated down time of key MDL equipment, 2014.

PROFESSIONAL SOCIETY DISTINCTIONS

1. G. Chattopadhyay was selected as IEEE MTTS Distinguished Microwave Lecturer.
2. N. Llombart, M. Alonso-DelPino, C. Lee, G. Chattopadhyay, C. Jung-Kubiak, and I. Mehdi, 2014 THz Science and Technology Best Paper Award, IEEE Microwave Theory and Techniques Society, for a paper entitled "Silicon Micromachined Lens Antenna for THz Integrated Heterodyne Arrays."
3. B. Karasik was elected to the Board of Directors of the Applied Superconductivity Conference.
4. J. V. Siles was elected Director of Academic Outreach of the Fulbright Association – Greater LA Chapter, elected by the Fulbright Association Board on September 2014, Los Angeles, CA.
5. J. V. Siles was elected Vice-Chair of the IEEE MTT-S Metropolitan Los Angeles – San Fernando Valley Chapter.
6. I. Mehdi is topical Editor for IEEE TST.
7. G. Chattopadhyay is topical Editor for APS.
8. Shouleh Nikzad was elected as the President of the Society for Brain Mapping and Therapeutics (SBMT). SBMT president serves for one year and co-chairs the annual congress of the society.
9. Doug Bell and Shouleh Nikzad, together with Nader Engheta (University of Pennsylvania), organized and led a workshop to explore the potential impact of metamaterials on future ultraviolet and optical and other mission.
10. Shouleh Nikzad led the Medical Engineering study under the Blue Sky studies. She also delivered an invited talk at the Caltech Medical Engineering Inaugural Industry Day.
11. Shouleh Nikzad was named an associate editor for SPIE's new Journal of Astronomical Telescope, Instruments, and Systems. The journal features peer-reviewed manuscripts detailing "original research in the development, testing and application of telescopes, instrumentation, techniques and systems for ground- and space-based astronomy."
12. Shouleh Nikzad, et al., "The results of development of ALD-MgF2" was published in the *Journal of Vacuum Science and Technology* (JVSTA) special issue on Atomic Layer Deposition and was featured on the journal's website as an "Editor's Picks" choice.
13. Sarath D. Gunapala was elected 2014 IEEE Fellow for the advancement or application of engineering, science, and technology.
14. Sarath D. Gunapala was elected 2014 Optical Society of America (OSA) Fellow for outstanding contributions and leadership in the optics and photonics profession.
15. Sarath D. Gunapala was elected 2014 Fellow, Jet Propulsion Laboratory.
16. F. Marsili, et al., SNSPDs have been featured on the JPL newsroom — http://www.jpl.nasa.gov/news/news.php?feature=4384.
17. F. Marsili, et al., SNSPDs have been featured on the JPL computer weekly — http://www.computerweekly.com/feature/The-future-of-secure-comms-quantum-key-distribution.

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All work described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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