National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology

Microdevices Laboratory

PATHS TO THE FUTURE

2012 ANNUAL REPORT

Since 1989, MDL has provided end-to-end capabilities in design, fabrication, and characterization of advanced components and sensors. MDL research and development activities have produced seminal contributions to the microdevice technology revolution, and our novel and distinctive products enable remarkable achievements in NASA's space and Earth science programs. In addition, MDL products are used in numerous applications in support of other national priorities.

The work and contributions of the talented MDL scientists, technologists, and research staff hold the promise of further extensions of our ability to peer into the far reaches of our solar system, other galaxies, and the very beginnings of our universe.

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The research 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.

Visit us online at microdevices.jpl.nasa.gov

Artist's concept by Pat Rawlings.

MDL TECHNOLOGIES WILL HELP HUMANKIND TOUCH DISTANT WORLDS...

Human safety aboard spacecraft is a top priority as NASA continues to support the International Space Station and plans future missions. Early detection of harmful gases is vital to survival for the astronauts who live in these isolated environments. To help advance the next generation of gas-detection instruments, researchers at MDL are developing lasers that may one day help astronauts monitor gas levels while exploring Mars or other terrestrial bodies.

MDL TECHNOLOGIES WILL HELP CHANGE HOW WE WORK...

Imagine the ability to utilize a handheld smartphone or tablet-style chemistry lab for both professional or personal use. A chemistry “app” running on your device could monitor levels of different species or other substances in liquid samples. MDL is developing automated lab-on-a-chip capillary electrophoresis that could one day enable these forms of hand-held tools.

MDL TECHNOLOGIES WILL HELP US STAY SAFER...

Members of the United States armed services are often caught in difficult conditions with immediate dangers hard to see with the naked eye. They may one day have the added confidence and safety benefit of helicopters and other transportation vehicles equipped with infrared technology that will help them safely navigate these hazardous conditions. MDL is at the forefront of developing novel infrared devices key to these technologies.

MDL TECHNOLOGIES WILL HELP REVEAL OUR PAST...

A telescope powerful enough to look back 10 billion years is projected to be built by 2017 on a mountain in Chile. It will help us understand how the universe began by providing the visible remnants of galaxies that formed when the universe was young. It will help answer questions such as how stars were first formed, and under what circumstances chemical elements such as oxygen and carbon first appeared. MDL is at the forefront in developing the state-of-the-art superconducting detector arrays that will enable these new discoveries.

MDL TECHNOLOGIES WILL HELP US LIVE BETTER...

In addition to enabling future astrophysics, planetary, and heliophysics missions, MDL actively partners to extend the application of their advanced ultraviolet (UV) detector technologies to other fields including industrial applications and medical diagnostics. For example, UV cameras are currently in clinical trials that, in the future, may help neurosurgeons pinpoint cancerous cells unseen with the naked eye during operations.

LETTER FROM THE DIRECTOR

Whatever our personal view of the future, it will no doubt be framed in recognition of the role of highly capable new technologies that extend the human experience in exploration, sensing, safety, lifespan, communication, and creativity — a continued success story of infusion of MDL-developed technologies into projects of national interest.

With respect to Plato, who said that necessity is the mother of invention, at MDL we would refine that quote to say that creativity is the wellspring of the future. We have witnessed this success in the past and anticipate its pivotal role for the next decade as we peer into an exciting new world of breakthrough, game-changing technologies. This past year saw an explosion of achievements at MDL: in detector arrays from ultraviolet to infrared wavelengths; in laser sources for Earth emissions and planetary sensing; in advanced optics of unprecedented precision and efficiency; in superconducting materials and devices for revealing our place in the universe; in submillimeter-wave spectrometers for national security and planetary sensing; in nano- and microtechnologies for industry and defense that enhance our quality of life; in lab-on-a-chip analysis to explore liquid and icy worlds; and in next-generation microfluidic thrusters for space exploration.

We were privileged this year to welcome to MDL our Visiting Committee (see back cover) comprising leaders of government, industrial, and academic institutions who conducted a thorough review to assess the quality and content of MDL's scientific and technical research, to evaluate facilities and capital equipment plans, and to make recommendations on emerging new areas of research and technology infusion. The Visiting Committee — who recognized MDL as a key national asset with world-class staff and capabilities that are enabling and enhancing NASA's space missions — made important recommendations to ensure our long-term growth and success on our path to the future.

NASA's investment in the invention of the interband cascade laser at MDL paid off richly following the successful landing on Mars of the Curiosity rover in August 2012, when the JPL-built tunable laser spectrometer made new measurements of methane gas and key isotope ratios in hydrogen, carbon, and oxygen for gases in the Martian atmosphere and those evolved from heated soils and rocks.

MDL researchers and managers 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, Deputy Director Dr. Siamak Forouhar and I join our university, industrial, defense, and commercial partners in celebrating our incredible achievements to date across a diverse range of applications. Our trademark and inspiration for the future will remain in creative innovations in miniaturized technologies that contribute to the national interest.

Dr. Christopher Webster
Director
JPL Microdevices Laboratory

LETTER FROM THE DIVISION MANAGER

MDL's extraordinary microdevice and nano technologies have enabled JPL and NASA to carry out new types of observations and measurements in space and Earth science missions over the past two decades. Dedicated to continuing this tradition of innovation, we are looking forward to the next generation of exciting discoveries.

As I reflect back on the past decade and my association with JPL's Microdevices Laboratory, it's hard to envision the future contributions of the MDL to NASA's mission given the immense impact that it has had on the past. Some years ago, we strove to ensure that device technology development in the MDL be both relevant to and enabling of the NASA mission. With this focus, technologies from the MDL have allowed us to explore our planet, our solar system, and the universe in ways previously not possible. Whether one chooses examples like the multiblaze diffraction gratings used in spectrometers to understand our changing planet, thermopile detectors used to characterize Mars and the Moon, or spider-web bolometers used to study distant galaxies and study the earliest beginnings of star formation, the MDL has clearly put its imprint on the NASA mission of the last decade.

So what does the future hold and how will innovation from within the MDL impact what we will see next? This question is all but impossible to answer, as any answer you might be able to convince yourself as reasonable would certainly be shown to have been too conservative. The invention and innovation that occurs within the MDL is somewhat unpredictable, occasionally spectacular, but always focused on enabling observations that were previously thought unachievable.

Enabling innovation, however, does require investment in equipment and people. Over the course of the last year, we have made a significant investment in equipment for the MDL. Among the new capabilities that we brought online during the last year, two significant new capabilities have been added, including a Canon FPA 3000 deep-ultraviolet stepper and a Canon FPA3000 i-Line stepper. These machines will support our detector development from the infrared to much longer wavelengths into the terahertz range. We have also added a number of recent graduates to the staff working in the MDL supporting a wide range of areas of detector development, including our work with barrier infrared devices and UV-sensitive delta-doped silicon devices.

As a final note, we had our Visiting Committee composed of distinguished leaders from industry, government, and academia evaluate our capability and performance, as we do periodically. I was pleased as many reflected on our efficiency of operations given our unique breadth of capability. They recognized the MDL as a unique national asset with a world staff and capability and acknowledged the linkage of the innovation and invention from the MDL to the NASA mission, to the JPL mission, and to problems of unique national relevance. As you read through this year's MDL Annual Report I'm sure you will find, as I do, that great people can achieve great things given the right tools and environment.

Dr. Thomas S. Luchik
Manager
Instruments and Science Data Systems Division

The coastal zone is home to a high fraction of humanity and is increasingly affected by natural and human-induced events from tsunamis to toxic tidal blooms that can affect the wildlife mortalities of marine and coastal species and other organisms. This Landsat-5 satellite image in 2011 shows one of the worst algae blooms Lake Erie has experienced in decades. While current satellite data provide an overview of these events, they do not have the spectral, spatial, and temporal resolution to characterize and understand these events. To address this gap, an airborne Portable Remote Imaging Spectrometer (PRISM) (page 19) has been developed at JPL.

Landsat image created for NASA's Earth Observatory by Jesse Allen and Robert Simmon, using data provided courtesy of the United States Geological Survey.

OPTICAL COMPONENTS

MDL's precision optical devices are at the heart of instruments that realize new capabilities across wavelengths from the ultraviolet to far-infrared.

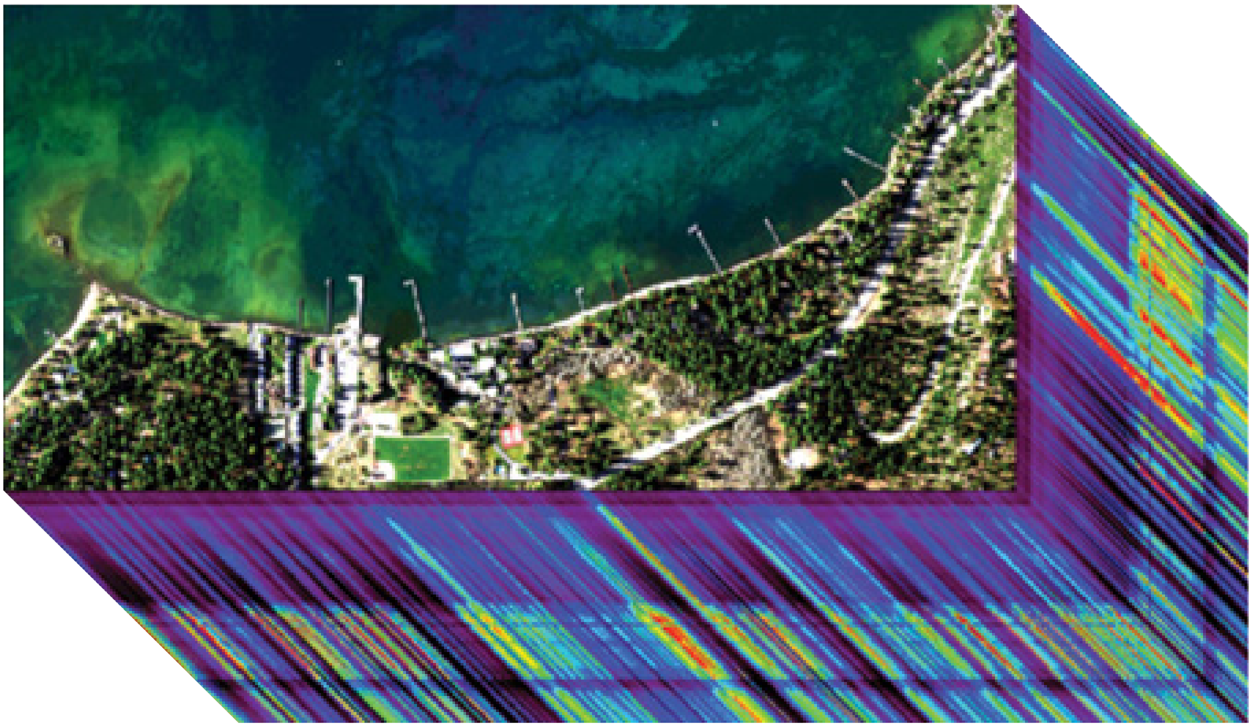
Electron-beam lithography techniques are developed to fabricate unique optics that enable JPL instruments to perform novel measurements and achieve unmatched performance. In addition to reliable binary nanopatterning processes, we have developed techniques for fabricating precision analog (grayscale) surface relief profiles in polymers 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 ultra-violet to long-wave infrared. Further, we have developed the capability to electron-beam fabricate these diffractive optics on nonflat (convex or concave) substrates with several millimeters of height variation. Our most important products are convex and concave diffraction gratings for Offner- and Dyson-type imaging spectrometers. These gratings have highly optimized blazed groove profiles that produce tailored spectral efficiency that equalizes the signal-to-noise ratio of the instrument over its operating wavelength range. >>

Large Computer-Generated Holograms for Meter-Class Telescope Integration and Testing

Meter-class telescopes comprising adaptive and segmented optics have ushered in a new "golden age" in observational astronomy, and highly lightweighted versions of these telescopes for spaceborne applications are under active development.

Optical testing of these complex optical systems presents their own set of unique challenges, one of which is the need to generate aspheric optical wavefronts with precision on the order of nanometers, maintained over meters of spatial extent, to serve as the reference standard in interferometric "optical null" testing. The critical optic in this type of testing is a computer-generated hologram (CGH), a lithographically patterned diffractive optical element that transforms a plane wavebeam into the desired spherical or aspherical wave that perfectly matches the design of the mirror or system under test. To address the need for larger CGHs than are available from commercial sources, MDL developed new electron-beam lithography capability to fabricate CGHs up to 230 mm in diameter with pattern placement accuracy in the tens of nanometers. This new capability required fabrication of a new e-beam cassette, measurement of e-beam placement accuracy, correction of e-beam placement errors, and development of new e-beam exposure and resist processing techniques. The larger CGHs will enable our partners to fabricate large mirrors and align segmented mirror systems to tighter tolerances than ever before. These large-aperture optical systems will enable new astronomical discoveries from ground and space.

Below: A 230-mm-diameter x 12-mm-thick computer-generated hologram fabricated by e-beam lithography at JPL MDL.

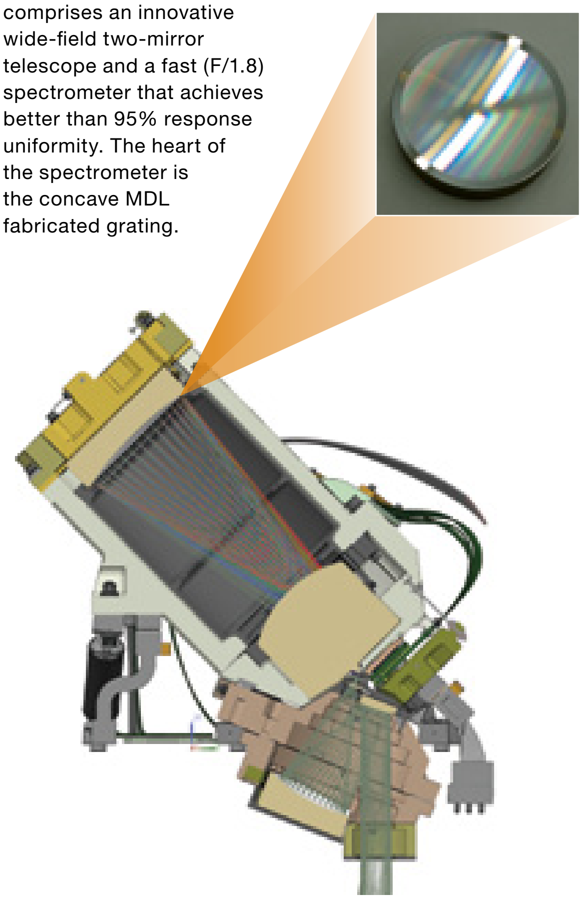


Above: PRISM spectral image cube of Lake Tahoe coastline. Each pixel has its spectrum recorded. The spectrum is indicated along the depth dimension for the perimeter pixels.

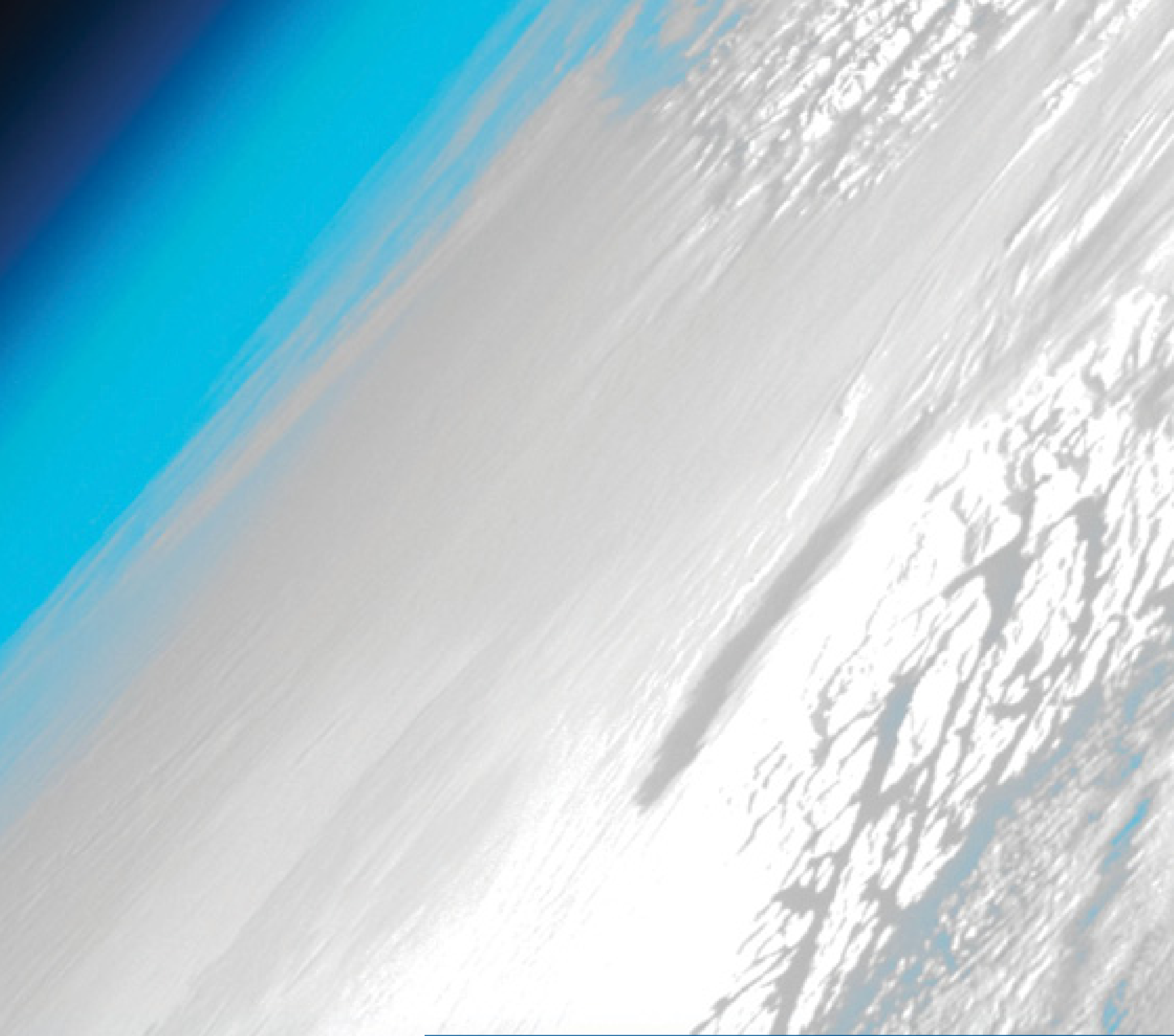
JPL's PRISM Will Help Expand Our Understanding of Natural and Human-Induced Events on Coastal Ecosystems and Communities

JPL's Portable Remote Imaging Spectrometer (PRISM) is designed to accurately measure ocean color for studying naturally occurring and human-induced events in coastal ecosystems and communities. PRISM is a fast Dyson-type imaging spectrometer for the visible and near-infrared (350 to 1050 nm) whose sensitivity, dynamic range, and polarization properties are specifically designed for the challenges of the coastal ocean environment. PRISM utilizes a shaped-groove concave grating designed and fabricated at MDL that provides high efficiency with low polarization sensitivity (less than 1%) to avoid issues with unknown atmospheric polarization. In May 2012, PRISM made its first flight on a NASA Twin Otter aircraft for test and calibration over Ivanpah Playa and Lake Tahoe. This was followed by a second flight over Monterey Bay in July. Under the guidance of Professor Heidi Dierssen, University of Connecticut, PRISM mapped the Elkhorn Slough area gathering data that will be used to understand the health of the seagrass ecosystem. Data analysis from both flights indicates excellent spectrometer performance.

JPL's PRISM optical system comprises an innovative wide-field two-mirror telescope and a fast (F/1.8) spectrometer that achieves better than 95% response uniformity. The heart of the spectrometer is the concave MDL fabricated grating.



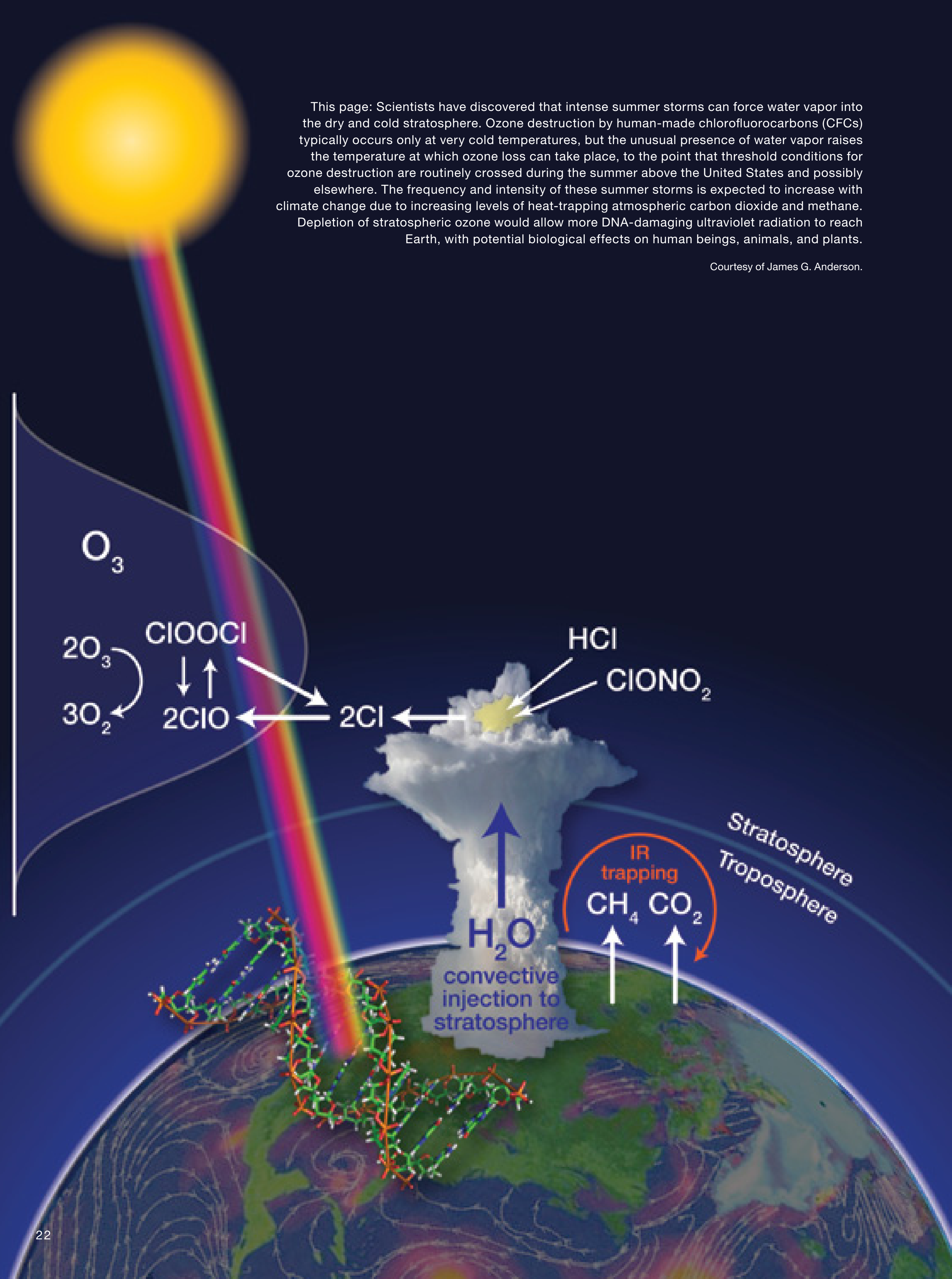
A photo of the Moon and Earth's atmosphere as seen from the International Space Station. In 2012, MDL delivered single-frequency 2.65-μm lasers that will help measure key atmospheric chemical species not easily accessible with current technology. The high-power lasers will allow measurements of H_2O and HDO concentrations in the stratosphere to study of the relationship between water vapor and mid-latitude ozone loss (page 22).



SEMICONDUCTOR LASERS

Laser-based MDL instruments capable of precisely measuring emission rates of carbon dioxide and methane on Earth are currently on the Curiosity rover carrying out similar analyses on the Martian surface.

JPL and NASA have a long history of flying tunable diode laser spectrometers on Earth and planetary missions for atmospheric and trace gas analysis. MDL has been involved in the design and fabrication of space-qualified semiconductor lasers since its inception. Of note, on November 2, 2012, NASA's Curiosity rover found clues to changes in the Martian atmosphere using an absorption spectrometer driven by a 3.27-μm semiconductor laser developed at MDL. With these initial sniffs of the atmosphere, the tunable laser spectrometer instrument made the most sensitive measurements ever to search for methane gas on Mars. Methane is of interest as a simple precursor chemical for life. On Earth, it can be produced by either biological or nonbiological processes. >>



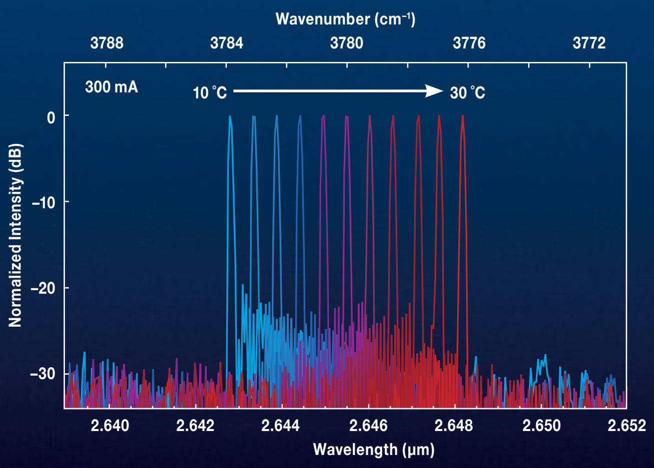
This page: Scientists have discovered that intense summer storms can force water vapor into the dry and cold stratosphere. Ozone destruction by human-made chlorofluorocarbons (CFCs) typically occurs only at very cold temperatures, but the unusual presence of water vapor raises the temperature at which ozone loss can take place, to the point that threshold conditions for ozone destruction are routinely crossed during the summer above the United States and possibly elsewhere. The frequency and intensity of these summer storms is expected to increase with climate change due to increasing levels of heat-trapping atmospheric carbon dioxide and methane. Depletion of stratospheric ozone would allow more DNA-damaging ultraviolet radiation to reach Earth, with potential biological effects on human beings, animals, and plants.

Courtesy of James G. Anderson.

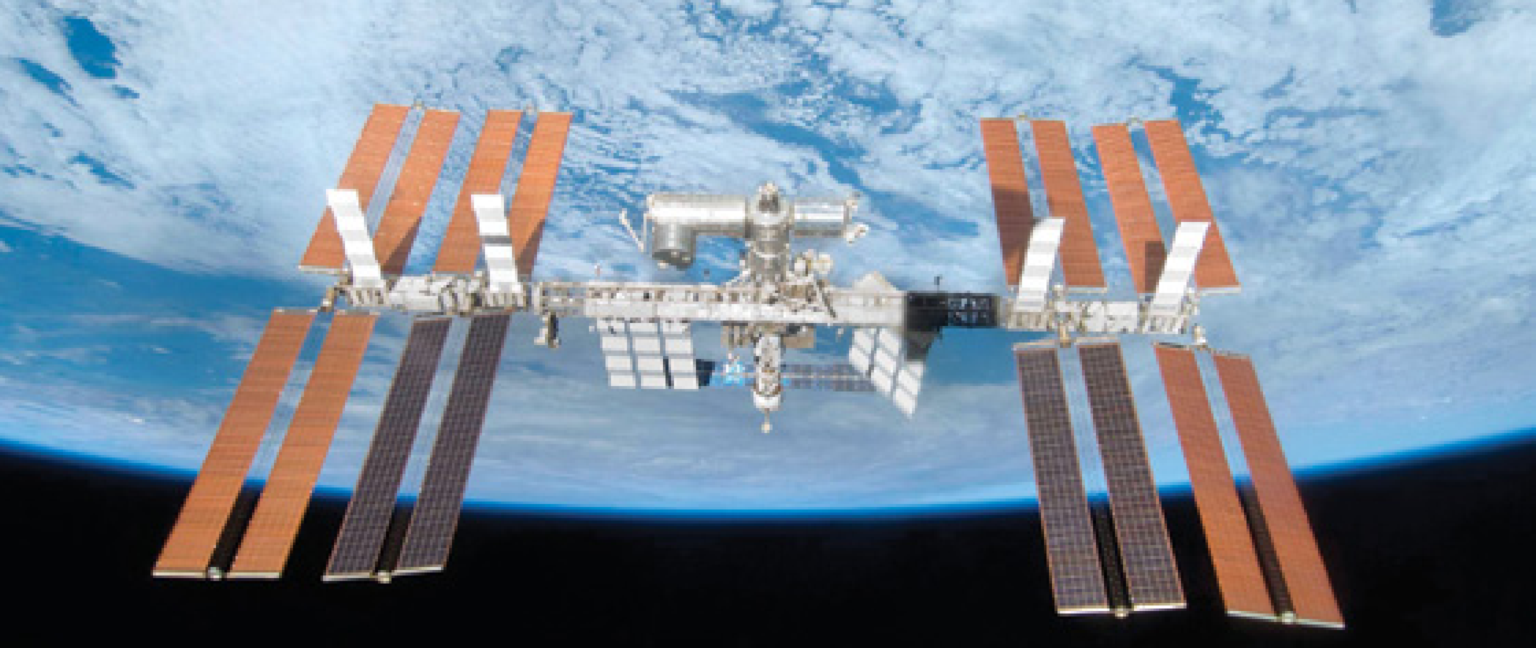
MDL Device Helps Support the Study of the Relationship Between Water Vapor and Mid-Latitude Ozone Loss

Recent calculations by Professor Jim Anderson's group at Harvard University show how increased surface temperatures can lead to a wetter stratosphere, resulting in mid-latitude ozone loss. Tools are needed to study the transport of water vapor into the stratosphere to better understand the dynamics and the subsequent chemistry of key halogens such as HCl and ClO in the event of a cold, wet stratosphere.

In 2012, MDL developed and delivered high-power, single-mode semiconductor lasers at 2.65-μm wavelength to Professor Anderson's team, as part of the NASA Advanced Component Technology (ACT) program to develop mid-IR laser instrument technology for measuring several key atmospheric species not easily accessible with current technology. The lasers produce more than 30 mW of output power — approximately three times the power specified for the airborne measurements, and an order of magnitude improvement over commercially available lasers at similar wavelengths. Professor Anderson's team is planning to incorporate these lasers into their instrument for airborne field experiments in the near future.



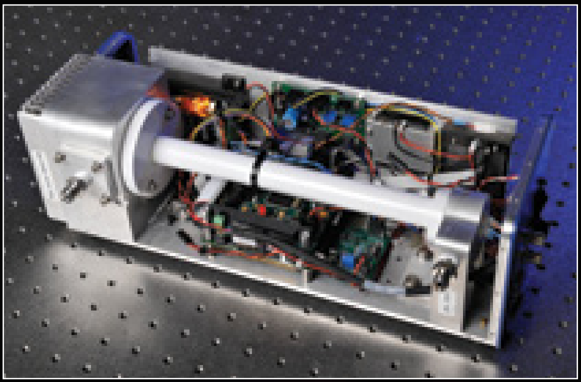
Above: Laser emission spectra measured over a range of operating temperatures, showing that the laser is continuously tunable over the H_2O/HDO line pair near 3777 cm^{-1}. Below: Packaged single-mode laser at 2.65 μm for detection of H_2O and HDO for the Harvard Total Water (HTW) instrument. HTW is designed to measure the sum of gas-phase and solid-phase water, or total water, in cirrus clouds, and to be mounted in a pallet in the underbelly of the NASA WB-57 research aircraft.



Laser Absorption Spectrometer for Fire Detection and Post-Fire Remediation

Crewmember safety aboard manned spacecraft is a top priority as NASA continues to support the International Space Station and plans future missions. In the confined and isolated environments that astronauts call home, early detection of harmful gases produced by combustion hazards and equipment malfunctions is essential.

To help advance the next generation of gas-detection instruments, researchers at MDL have developed single-frequency quantum cascade lasers to accurately monitor carbon monoxide (CO) levels using infrared laser absorption spectroscopy techniques. By tuning the laser wavelength across strong CO absorption lines between 4.6 and 4.8 µm, instruments can resolve parts-per-million levels of CO over interaction distances of a few centimeters, without interference from other gases. Furthermore, the lasers are designed specifically for continuous, stable operation with minimal electrical power consumption, allowing for maintenance-free monitoring of CO levels over the course of long-duration space missions.



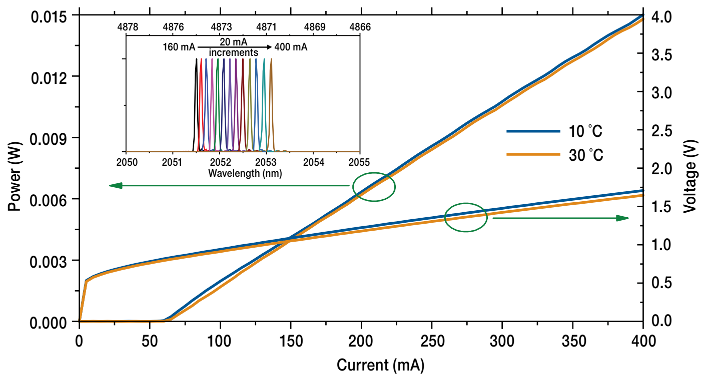
Above: Internal view of the JPL prototype CO sensor for crewed spacecraft safety. The instrument employs a tunable quantum cascade laser source with a 25-cm single-pass absorption cell. Below: The operational CO sensor enables accurate and continuous monitoring for early-warning fire detection and general environmental safety.

Semiconductor Lasers Will Help Measure Greenhouse Gases (GHGs) From Space

Measurement of regional and global CO_2 and CH_4 distribution and better understanding of the sources and sinks is essential in assessing their impact on global change.

Lidar instruments based on laser absorption spectroscopy (LAS) techniques are being developed that can be used to measure GHGs remotely either from an aircraft or an Earth-orbiting platform. The LAS instrument requires optical transmitters emitting mid-IR wavelength, high-energy pulses that are spectrally narrow and extremely stable.

A common technique to achieve narrow-linewidth, high-power, and low-noise radiation is injection seeding, in which the output of a single-frequency, stable seed laser is coupled into the cavity of a much larger laser; inspiring the larger laser to lase in a single frequency dictated by the seed laser. Semiconductor lasers are attractive candidates as injection seeds due to their compact size, high efficiencies, and superior reliability. However, lasers capable of generating the mid-IR radiation, the desired wavelength for GHG absorption, are not readily available. MDL has developed semiconductor lasers operating in the 2- to 3-μm range with record high output power and narrow linewidth. The optical-fiber-coupled seed lasers under development will enable robust all-fiber lidar transmitters.



Above: Light output and electrical performance measured for a fiber-coupled semiconductor laser developed at MDL for CO_2 detection near 2.05 μm.

Below: University of Alaska research assistant professor Katey Walter Anthony ignites trapped methane from under the ice in a pond on the Fairbanks campus. As ice thaws due to rapid warming in the Arctic, massive amounts of greenhouse gases trapped below the surface will likely vent into the air over the next several decades, with the potential to accelerate and amplify climate change.

University of Alaska Fairbanks photo by Todd Paris.

A nighttime photograph shot from the International Space Station of the Aurora Borealis as the outpost flew over the Midwest. The Magnetosphere Ionosphere Coupling in the Alfvén Resonator (MICA) mission launched in Alaska in 2012 as part of a NASA-funded study to study aurorae. Enabled by an MDL-developed device (page 28), the mission's goal is to gather insights into how the Sun's energy interacts with Earth's magnetic field, which can affect signals from global positioning system (GPS) satellites and other spacecraft.

ADVANCED VISIBLE AND ULTRAVIOLET DETECTORS AND IMAGING SYSTEMS

Advances generated at MDL will extend our vision to unprecedented sensitivity of low light levels that will enable unimagined future discoveries and capability.

Researchers at MDL develop high-performance detectors using nanoscale bandstructure engineering, employing epitaxial techniques, including molecular-beam epitaxy (MBE) and atomic layer deposition (ALD). For example, applying these processes to fully fabricated silicon imaging detectors such as charge-coupled device (CCD) and complementary metal-oxide semiconductor (CMOS) arrays, MDL has achieved 100% internal quantum efficiency (QE) with JPL-invented delta-doping and new superlattice doping techniques. Combining MBE processes with novel antireflection coatings using ALD, we have demonstrated reliable performance in QE in the UV. MDL is applying surface and interface engineering using epitaxial techniques to other materials and detector systems such as gallium nitride and its alloys for detector and photocathode configurations. In addition to enabling future astrophysics, planetary, and heliophysics missions, MDL also partners to extend the application of our detectors to other fields such as medical diagnostics and industrial process inspections. >>

Insights into How Solar Wind Interacts with Earth's Magnetic Field

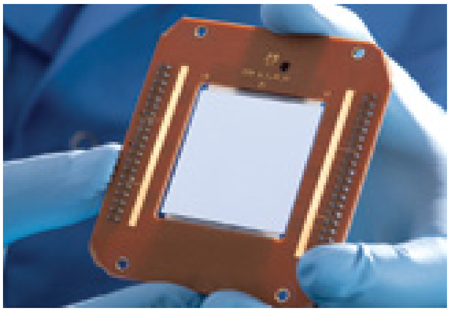
The Magnetosphere Ionosphere Coupling in the Alfvén Resonator (MICA) mission was launched from the Poker Flat Research Range in Alaska on February 19, 2012, as part of a NASA-funded study. The mission's goal is to gather insights into how the solar wind interacts with Earth's magnetic field, which can affect signals from global positioning system (GPS) satellites and other spacecraft.

MICA used several instruments, including the Southwest Research Institute's low-energy electron-spectrometer (LEES). LEES was enabled by an MDL-developed delta-doped 1kx1k low-energy electron detector. Delta-doping improves the low-energy electron detection threshold by an order of magnitude and simplifies and improves instrument performance. It also removes the need for massive power supplies, allowing for a more compact instrument.

Scientists and students representing Cornell, Dartmouth College, Southwest Research Institute, JPL, the University of New Hampshire, and the University of Oslo participated in the study.

Photograph by Terry E. Zaperach, NASA.

Rocket Experiment Paves the Way for Future Studies of Exoplanetary Systems and Galaxy Formation

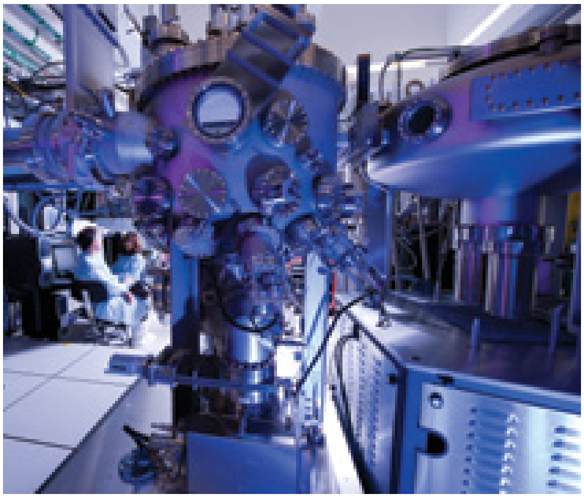


A key astrophysical theme that will drive future UV/optical space missions is the life cycle of cosmic matter, from the flow of intergalactic gas into galaxies to the formation and evolution of exoplanetary systems. The Colorado High-resolution Echelle Stellar Spectrograph (CHESS) is a rocket-borne instrument that will serve as a pathfinder for future high-sensitivity, high-resolution UV spectrographs. MDL delivered a CCD (right) to Arizona State University (ASU) for integration into a flight-ready camera for CHESS. The CCD is to operate in the 190-nm region and has higher efficiency than the image tube–based devices that previously have been used in UV instruments. Work is currently underway at ASU for integration and testing of the camera.

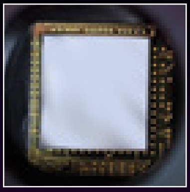
Above right: MDL's delta-doped, 3.5kx3.5k 10.5-μm-pixel CCD was delivered to ASU for integration into a flight-ready camera for CHESS.

MDL Completes Full Commissioning of its 8-inch Silicon Molecular-Beam Epitaxy (MBE) for Production of Large-Area Silicon Scientific Imaging Arrays

Because of MBE's exacting requirements for temperature calibration, deposition rate, and dopant incorporation calibrations, special features were added or modified to MDL's 8-inch silicon MBE in collaboration with Veeco as a first-of-its-kind machine. The 8-inch silicon MBE was fully commissioned for production of large-area silicon scientific imaging arrays at high throughput and high yield. Devices were fully characterized to ensure that they were effectively delta-doped. The MDL team also worked with Lawrence Berkeley National Laboratory (LBNL) to demonstrate n-type delta-doping on LBNL's devices at wafer level and produced 12-megapixel, delta-doped p-channel CCDs. These wafers were probe tested at LBNL, showing 63% science-grade devices.



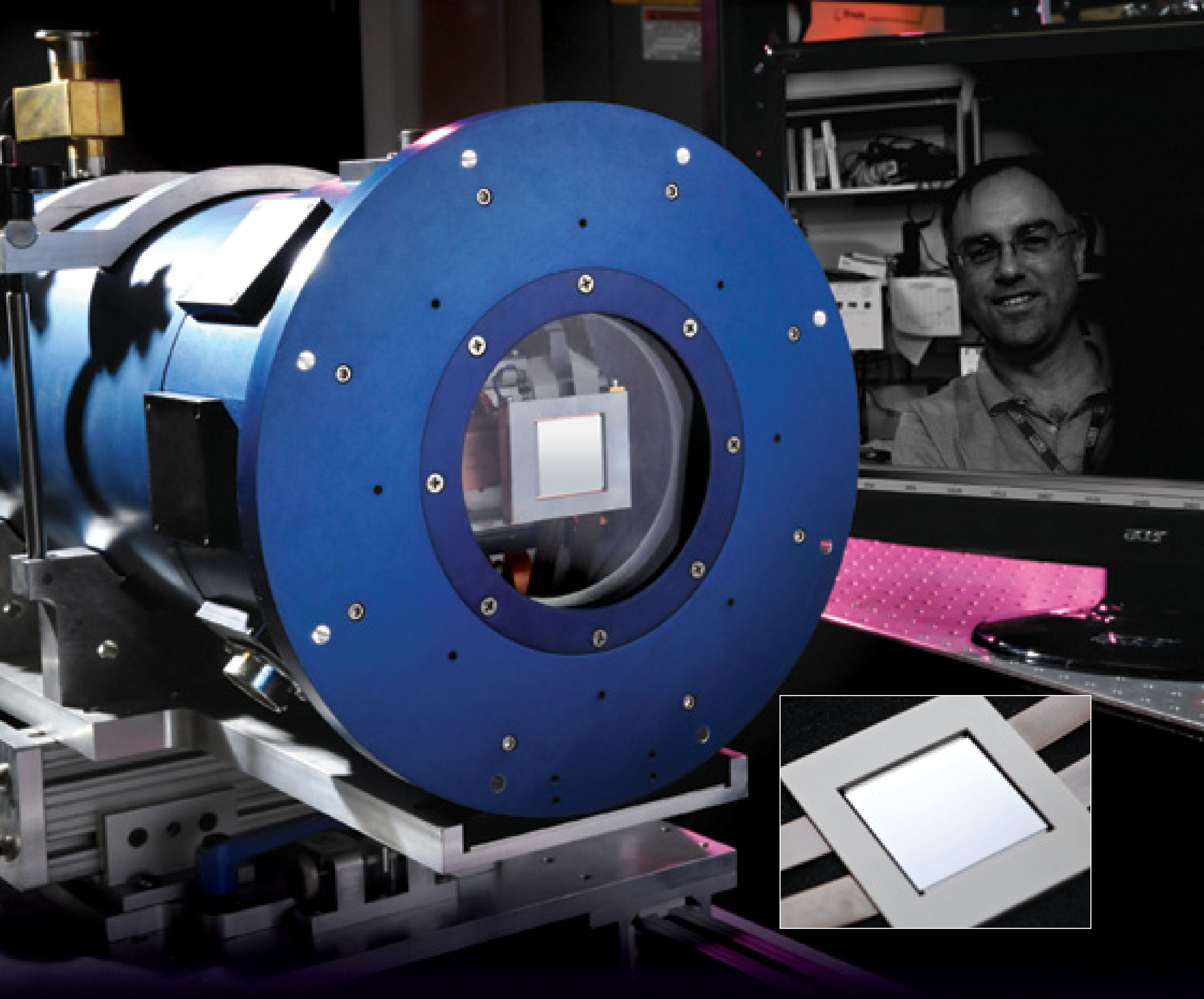
Superlattice Doping Enables Unprecedented Stability to Ionizing Radiation



In 2003, one of the industry leaders in CCD manufacturing wrote about the quest for stable deep-ultraviolet (DUV) CCDs, noting that existing DUV detectors suffer from an exponential increase in dark current with exposure to these high-energy photons. Because DUV radiation causes cumulative damage to the $Si–SiO_2$ interface, surface passivation is the key to stability.

Working with Alacron Inc. (research arm of FastVision), JPL researchers processed 8-inch-diameter CMOS wafers for back illumination using MDL's production-scale MBE and ALD systems to produce DUV devices with unprecedented stability. In lifetime tests performed by one of the industry leaders in semiconductor manufacturing systems, these superlattice-doped detectors were exposed to several billion excimer laser pulses at 263 nm and 193 nm. MDL's new superlattice-doped, antireflection-coated CMOS detectors achieved 64% peak QE at 263 nm, and are the only imaging detectors known to have survived direct, long-term exposure to excimer lasers with no measurable degradation in performance. Alacron Inc. has licensed this technology for use in advanced semiconductor inspection systems.

Above: JPL/Alacron Inc.'s high-speed 3-megapixel superlattice-doped CMOS camera. Inset: Superlattice-doped, antireflection-coated CMOS imaging array.



JPL's Deployable Delta-Doped Cameras for On-Sky Measurements

As part of demonstrating capabilities of delta-doped arrays in relevant scientific environments, MDL developed two easily deployable cameras for field testing at ground-based observatories. The cameras will be used in on-sky measurements to detect star-forming regions in nearby galaxies, supernovae and other transient objects, and objects with faint UV/optical/near-infrared signatures. MDL designed, developed, and produced a delta-doped CCD traveling camera capable of operating in photon-counting mode for ultra-faint target applications. This camera is equipped with a versatile cryostat and electronics that can operate delta-doped devices of various formats and designs (e.g., broadband fully depletable arrays or photon-counting arrays). The camera can be easily interfaced with observatory facilities.

The first devices integrated into the cameras for laboratory system checkout were a 4-megapixel delta-doped broadband CCD and a 0.5-megapixel delta-doped photon-counting CCD produced under the 8-inch silicon MBE commissioning effort. MDL scientists plan to work with various principal investigators and deploy the traveling camera for a series of technology and science expeditions.

Above: MDL's traveling camera equipped with a delta-doped, 2kx2k 15-μm pixel CCD (inset).

KISS Study Advances Concepts for Next-Generation Ultraviolet Instruments

UV offers one of the few remaining areas of the electromagnetic spectrum where it is possible to make great leaps in instruments and science return. In support of the advancement of next-generation UV/optical missions, the W. M. Keck Institute for Space Studies (KISS) selected Shouleh Nikzad from JPL's MDL, Professor Chris Martin from Caltech, and Professor David Schiminovich from Columbia University to lead a study for the creation of a new paradigm in UV/optical instrument design, detector technology, and optics. This was a particularly timely study due to ongoing discoveries from missions such as Galaxy Evolution Explorer (GALEX), Hubble Space Telescope, and Cassini.

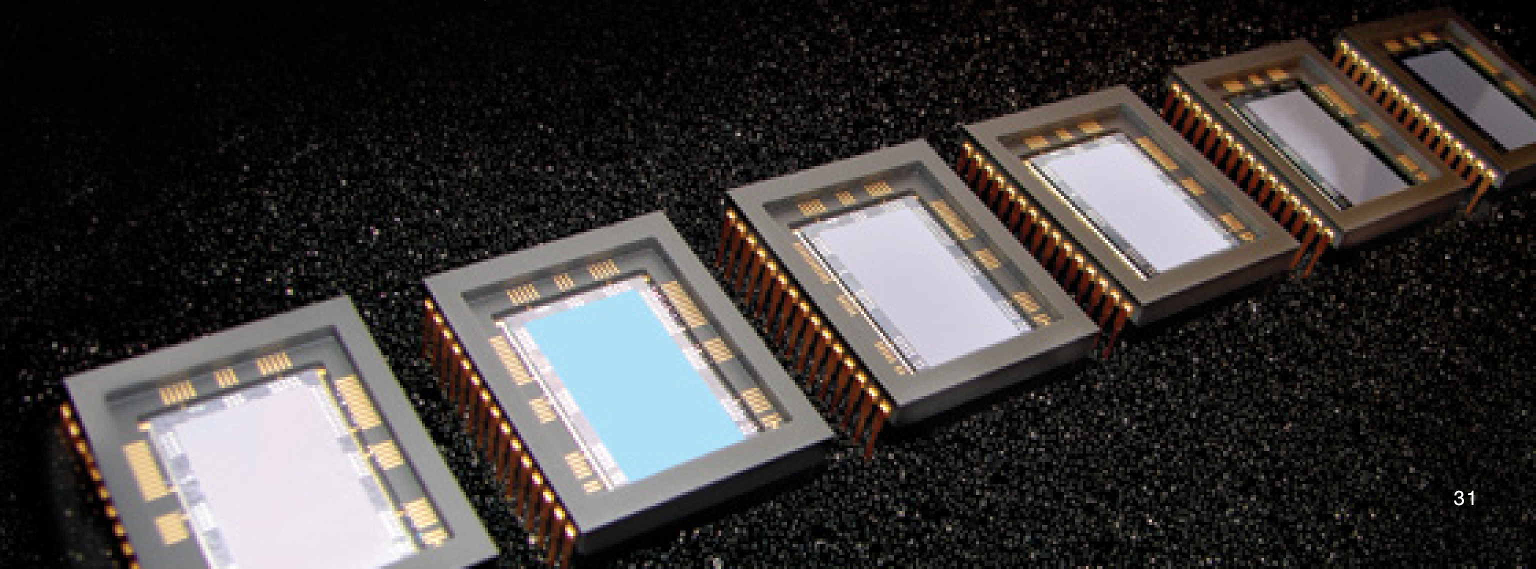
Participants for the study were selected from universities, other NASA centers and national laboratories such as NIST, and industry. The study brought together a diverse international community of students, postdocs, astrophysicists, cosmologists, materials scientists, device physicists, heliophysicists, and condensed-matter physicists. It led to many new ideas and collaborations, brought cohesion to UV practitioners, and created a comprehensive report on the science and technologies. All this will have a lasting and positive impact on the future of UV instrumentation.

A principal conclusion of the study was that UV detector performance drives every aspect of the scientific capability of future missions, and that two technologies were at tipping points for major breakthroughs. One of these is the atomic layer deposition, antireflection coated, delta-doped photon-counting detectors currently in development at MDL.

Faint Intergalactic Redshifted Experiment Balloon (FIREBall) Enabled by MDL's Next-Generation Detector

The Faint Intergalactic Redshifted Experiment Balloon (FIREBall), a Caltech mission to discover and map faint emission from the intergalactic medium, has been funded for a third launch by NASA. This mission will be enabled by a next-generation detector under development at MDL. The first two launches of FIREBall used a GALEX spare microchannel plate detector. The next-generation detector is a delta-doped, electron-multiplied CCD (EMCCD) further enhanced with custom antireflection (AR) coatings. This combination creates a detector that is capable of photon counting and possesses a quantum efficiency (QE) that is over an order of magnitude higher than the GALEX detector. While MDL's previously reported results showed >50% QE, MDL scientists are now working toward an even higher QE. FIREBall is an ideal testbed for delta-doped EMCCDs. We modeled an optimized AR coating design for 205 nm, an atmospheric window in the balloon flight. With this optimized multilayer coating, we have demonstrated over 80% QE in this range.

Below: Six fully processed and packaged 0.5-megapixel, delta-doped EMCCD devices. The device with the multilayer AR coating (<0.3 µm thick) for FIREBall is visibly darker in the photo.



Fueled by drought and high winds, a wildfire burns through the night in the Davis Mountains near Fort Davis, Texas. This and other fires burned throughout 2011 in west Texas.

The impact of global biomass burning on the terrestrial biosphere and atmosphere, and how its impact may change over time, is not fully understood. The Hyperspectral Thermal Emission Spectrometer (HyTES) will be the premier airborne thermal imaging spectrometer for Earth science. HyTES will be useful in studying the effects of wildfires and volcanoes on Earth's climate, water use and availability, and urbanization, as well as land use and habitability. Read more about MDL's contribution to this instrument on page 35.

INFRARED PHOTONICS

MDL's precision optical devices are at the heart of instruments that realize new capabilities across wavelengths from the ultraviolet to far-infrared.

MDL performs cutting-edge research and development in innovative IR detectors, focal plane arrays, and infrared cameras for space and terrestrial applications. The strength of the JPL team 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. JPL's work in the areas of quantum-well infrared photodetectors (QWIPs), quantum-dot infrared photodetectors (QDIPs), and superlattice detectors is well documented in the scientific literature in over 250 journal and proceedings papers and over 300 conference presentations. Among the team's 22 U. S. patents are key infrared technologies that are being adopted by leaders of infrared industry in the country. >>

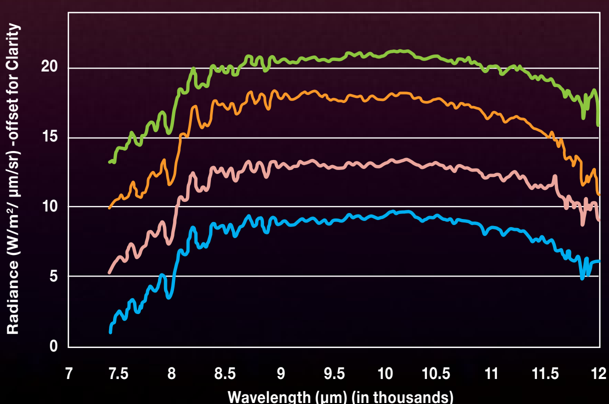
Large-Area Antimonides-Based Focal Plane Arrays

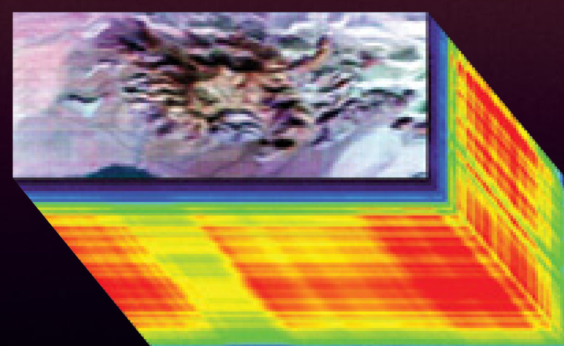
There are many critical steps in achieving high-performance and highly uniform large-area infrared focal plane arrays. The most critical steps are the quantum mechanical device design, molecular-beam epitaxial (MBE) growth of antimonides-based device structure, fabrication of large-area detector arrays, hybridizing them with CMOS readout integrated circuits, and removal of the original epitaxial substrate. MBE is a method of depositing single-crystal materials on large-area substrates. Over the years, MDL has developed techniques to grow the highest minority carrier lifetime antimonides-based epitaxial material. The challenge is to fabricate highly uniform, large-area detector arrays to support the next generation of large-aperture space-borne telescopes. We developed new lithography and array hybridization capability at MDL to fabricate 4-megapixel focal plane arrays with 10 microns pixel pitch. This required high-precision fabrication tools such as an i-line stepper, an inductively coupled plasma dry etching tool, large-area flip-chip bonder, an atomic layer deposition system, and a single-point fly-cutting diamond point turning tool.

Above: A JPL MDL engineer operates the Ontos-7 oxide removal machine for removing oxides formed on the indium bumps deposited on the pixels of a large-area infrared detector array prior to array hybridization process. Oxide removal helps the detector array hybridization process via indium cold weld with the silicon CMOS readout integrated circuits.

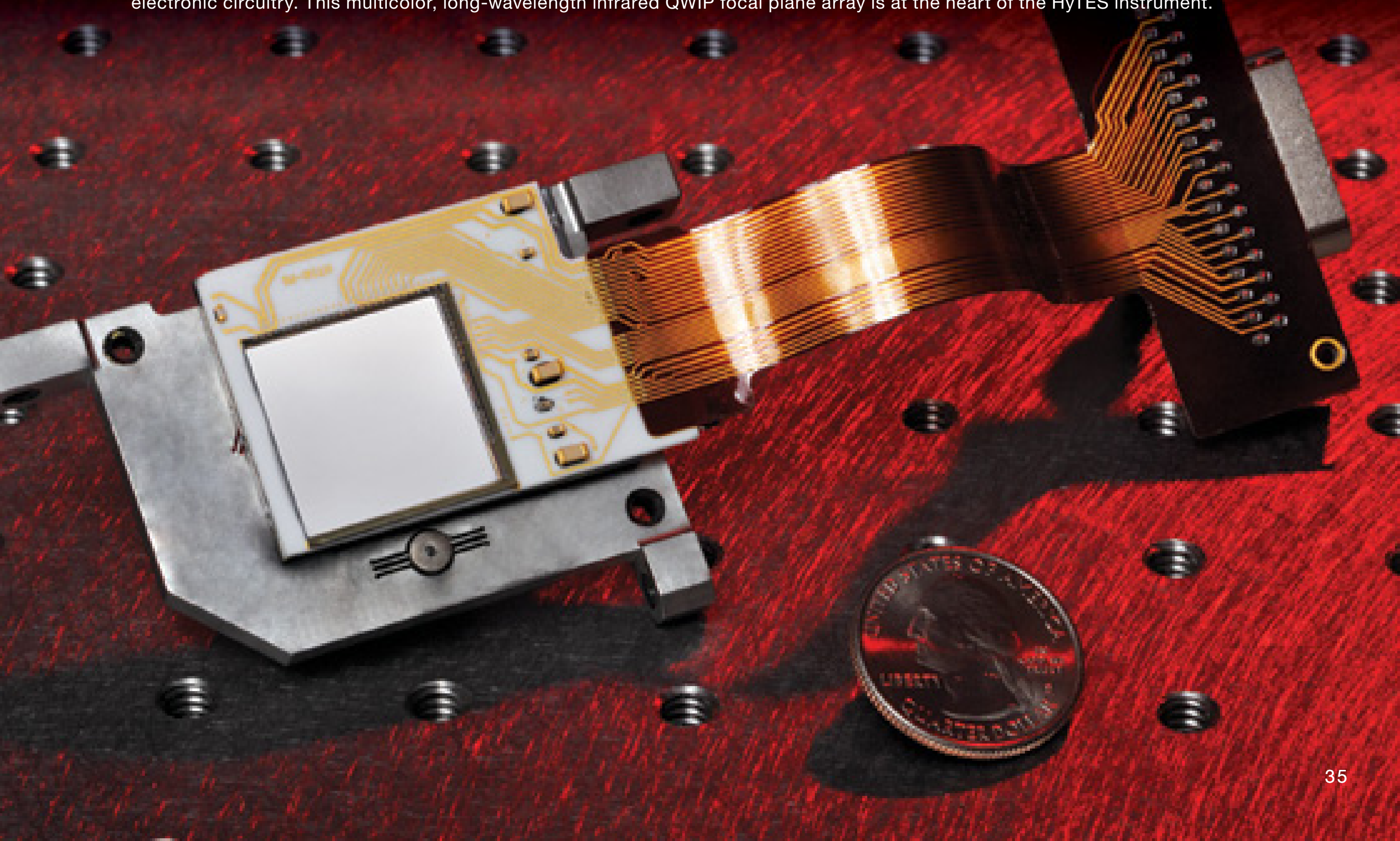
Premier Spectrometer for Earth Science Successfully Completes Laboratory Calibration and Performs First Engineering Flights

HyTES, a compact, high-throughput Dyson-relay imaging spectrometer for the long-wave infrared (7.5 to 12 microns), will be the premier airborne thermal imaging spectrometer for Earth science. MDL provided three key components that were successfully integrated into HyTES: a high-efficiency e-beam fabricated concave grating, an ultra-straight and uniform micromachined slit, and a broadband-response quantum-well infrared photodetector (QWIP) array. In 2012, HyTES successfully completed laboratory calibration and performed its first engineering flights over various sites between Grand Junction, Colorado, and the Salton Sea, California. These included Cuprite, Nevada, and Algodones Dunes in California. Flying over these basic calibration sites allows the HyTES team to understand the adjustments needed for the follow-up science flights that will be undertaken in 2013.





Above left: Radiance at sensor for different locations showing atmospheric features. Right: Cuprite, Nevada, July 20, 2012, bands 150 (10.08 µm), 100 (9.17 µm), 58 (8.41 µm) displayed as RGB, respectively, as image cube. Below: A nine-color megapixel QWIP focal plane array assembly with its daughter board and wiring harness, which connects the focal plane array with external electronic circuitry. This multicolor, long-wavelength infrared QWIP focal plane array is at the heart of the HyTES instrument.



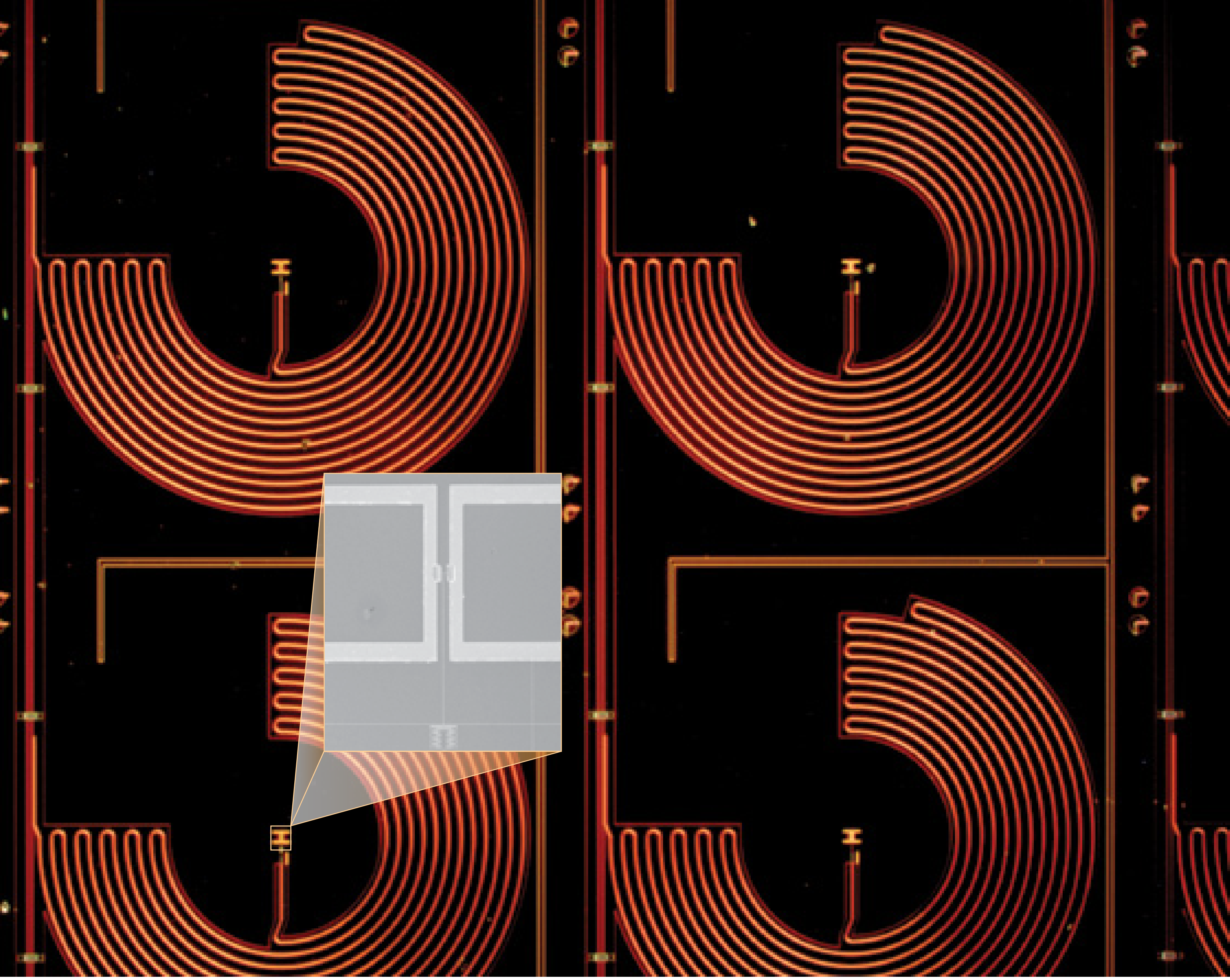
MDL initiated a collaboration with the Owens Valley Radio Observatory in 2011 to investigate whether its new amplifier (page 40) could greatly improve current state-of-the-art heterodyne receiver systems. In 2012, development expanded to include the design of a millimeter-wave version of the amplifier and the study of its potential applicability for the Atacama Large Millimeter Array (ALMA), currently the largest astronomical project in existence.

© Babak Tafreshi, The World at Night.

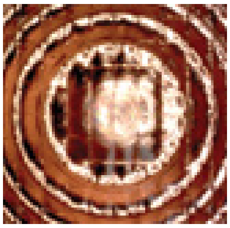
SUPERCONDUCTING MATERIALS AND DEVICES

Scientists continue development of devices that detect the cosmic microwave background and the elemental composition of distant galaxies during the formation of the universe, and at home map Earth's radiation balance and empower our new telescopes.

MDL develops advanced cryogenic millimeter and submillimeter detectors for spectroscopy, imaging, and polarimetry measurements in astrophysics. JPL has been a pioneer in the development of superconducting detectors for far-infrared/submillimeter astrophysics for 25 years. Initially, this effort focused on superconductor-insulator-superconductor mixers for heterodyne receivers for high-resolution spectroscopy, used on ground-based telescopes around the world as well as on current and planned NASA flight missions. Recent development efforts have been focused on large-format arrays of direct detectors for spectroscopy, imaging, and polarimetry for astrophysics and application of these technologies for Earth and planetary science. >>



Record Optical Performance with Quantum Capacitance Detector (QCD)



Photon-noise-limited detection of radiation in the submillimeter and far-infrared regions of the electromagnetic spectrum is a goal being pursued using a number of detector concepts. This performance makes the QCD ideal for future cryogenic far-IR missions such as Space Infrared Telescope for Cosmology and Astrophysics (SPICA), Millimetron, Single-Aperture Far-Infrared observatory (SAFIR), and Space Infrared Interferometric Telescope (SPIRIT), which will require moderate-resolution far-IR spectrometers operating at the photon background limit.

The quantum capacitor detector being developed at MDL relies on measuring quasiparticles generated by Cooper-pair breaking in a superconducting absorber using the change in capacitance of the single Cooper-pair box, a device originally developed for quantum computing. In 2012, a novel way of calibrating the power absorbed by the detector was devised, and measurements showed that the detector is photon-shot-noise-limited over 5 orders of magnitude in power. At 1×10^{-19} W optical loading, a world record optical noise equivalent power (NEP) 2×10^{-20} W/rt Hz was demonstrated.

The QCD array was integrated with a planar Fresnel lens array with e-beam writing fabricated at MDL.

Above: Four pixels of a 5x5 QCD array showing a double dipole antenna with absorber at its center. The lens array is placed on the back of the detector array die. Inset: A Fresnel lens array element that has been integrated into the QCD.

Support Continues for the Study of the Cosmic Microwave Background at the South Pole

Polarization-sensitive bolometers are currently in use to study the polarization of the cosmic microwave background (CMB) in two Antarctic missions, the BICEP2 telescope and the Keck multitelescope experiment. These missions continue to map the polarization signal of the CMB to gain evidence for inflation and hints of gravitational waves during the initial formation of the universe.

In 2012, MDL increased the optical efficiency of our science-grade arrays by ~1.5 times. These more efficient detector arrays were hybridized into the Keck experiment and placed into two of the five science-grade focal planes that are now deployed and observing the CMB.

Each focal plane unit (FPU) consists of four 150-GHz focal plane arrays that are fabricated at MDL. A focal plane array contains 64 dual-polarization pixels for a total of 512 pixels in each FPU.

Each pixel absorbs radiation from the CMB using a phased array of slot antennas, then transfers the absorbed radiation via a niobium superconducting strip-line to a thermally isolated termination resistive element. On the thermally isolated membrane, a superconductive transition-edge sensor (TES) is employed to measure the change in temperature of the isolated membrane. The TES elements are measured using a multiplexed superconducting quantum interference device (SQUID) ammeter from NIST.

Below: A view of all five Keck telescopes installed at the South Pole (March 2012). A 512-element, dual-polarization TES focal plane unit was installed into each of the five telescopes with each focal plane unit consisting of four arrays fabricated by MDL.

Photo courtesy Robert Schwarz.

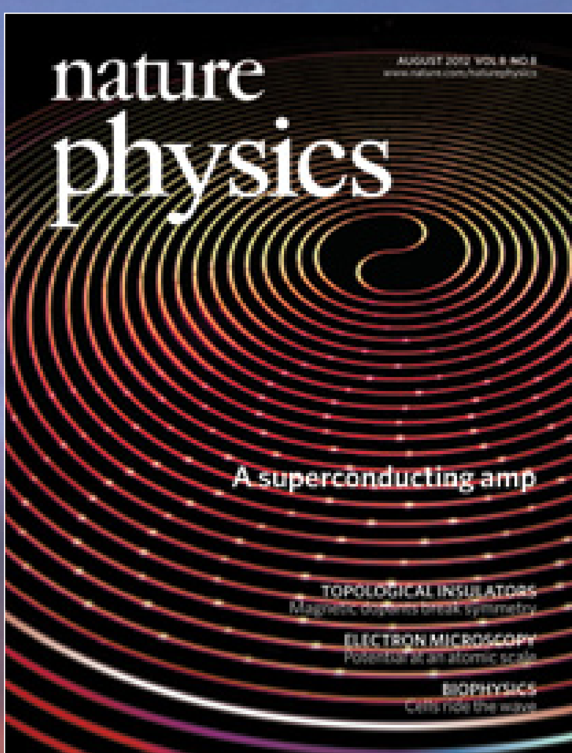
Superconducting Parametric Amplifier Demonstration Featured in *Nature Physics*

Continuing MDL's collaboration with the Owens Valley Radio Observatory to investigate whether its new amplifier could greatly improve current state-of-the-art heterodyne receiver systems, a broadband parametric amplifier operating at 10 GHz using niobium titanium nitride (NbTiN) was demonstrated in 2012.

A New Technology Report was awarded for this concept and the results of prototype testing were featured in the August issue of *Nature Physics*. The primary disadvantage of previous implementations of parametric amplifiers has been their limited bandwidth. The traveling-wave parametric amplifier developed at MDL has approximately 10 dB of gain over an octave at 10 GHz and a noise temperature <2 K, which is near the quantum limit.

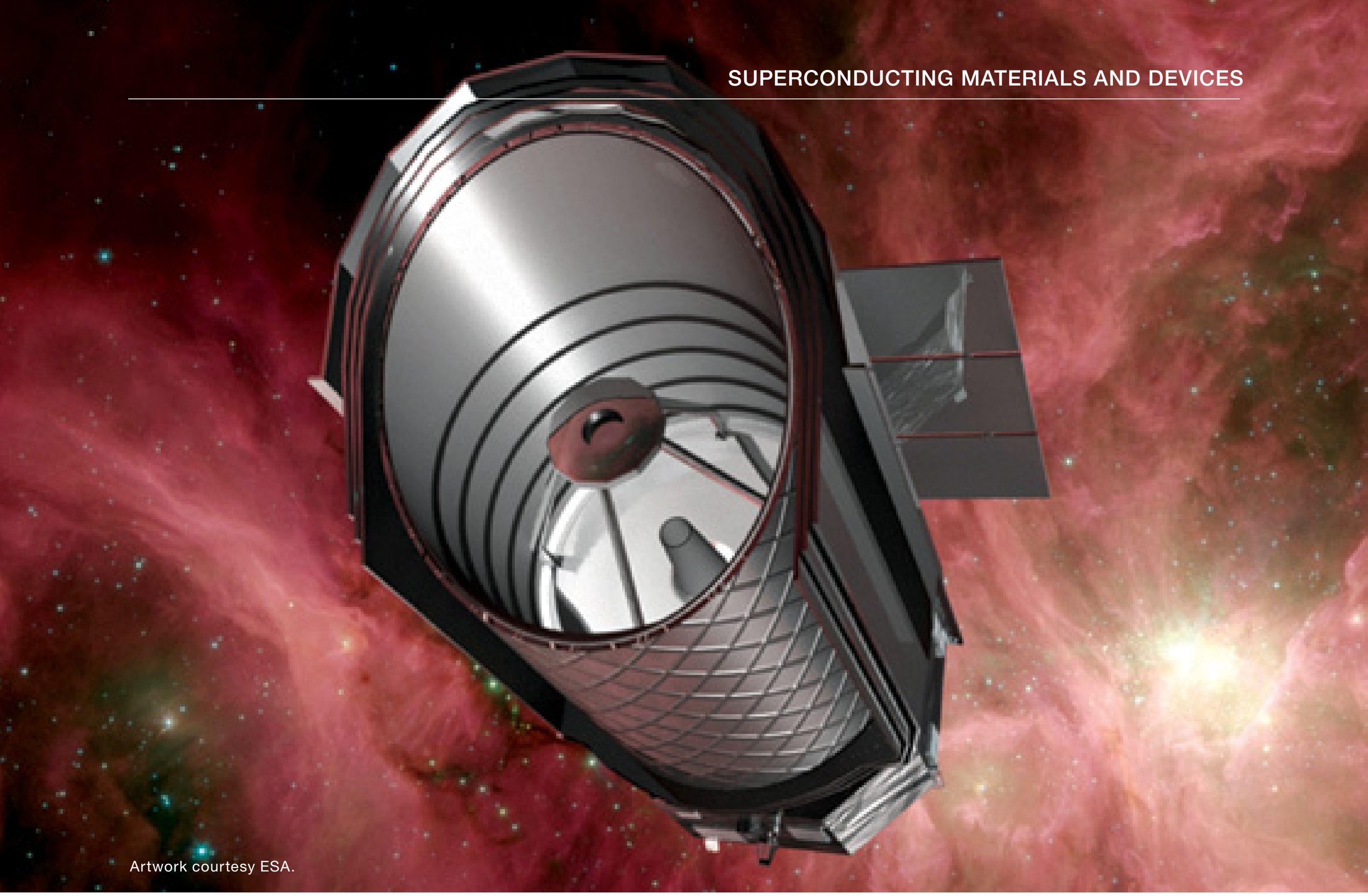
Parametric amplifiers of this type can operate at higher frequencies as long as the in-band loss is small. For superconductors, the loss should remain low up until a significant fraction of the gap frequency (720 GHz for Nb and 1400 GHz for NbTiN).

In 2012, an Atacama Large Millimeter Array (ALMA) Development Study was funded by the National Radio Astronomy Observatory (NRAO) to design a millimeter-wave version of the amplifier and to study its applicability to an upgrade of ALMA's band 3 and possibly other bands. By decreasing receiver noise temperature by at least a factor of 2, and bandwidth by a factor of 5, MDL's parametric amplifier could have a tremendous impact on ALMA science.



Above: MDL's superconducting parametric amplifier made of NbTiN was featured on the cover of the August 2012 issue of *Nature Physics.* This page: Partnership and testing continues with the Owens Valley Radio Observatory.

Photo courtesy Erik Leitch, Owens Valley Radio Observatory.

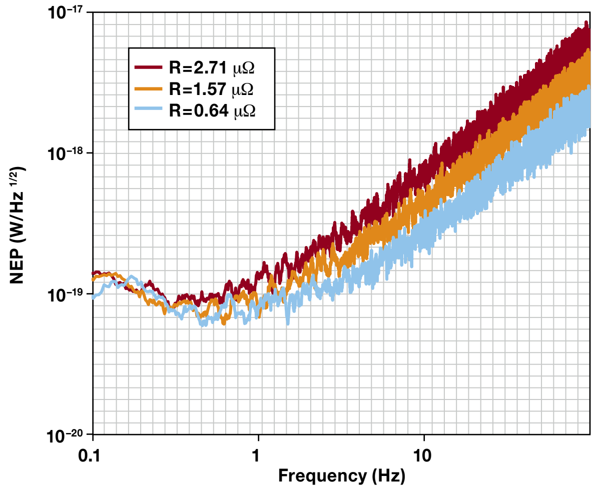


Artwork courtesy ESA.

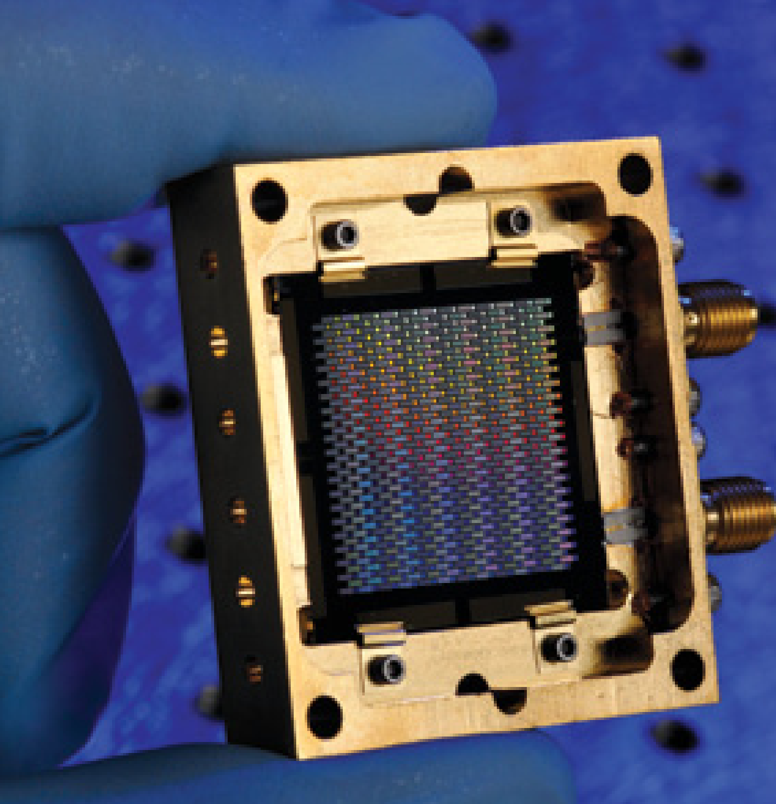
MDL's Transition-Edge Sensors May One Day Help Unlock Details of Our Cosmic Origins

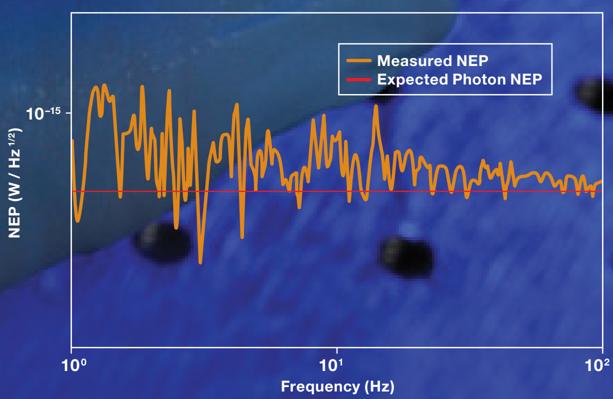
Current spaceborne infrared submillimeter instruments have imaged and studied the spectra of nearby galaxies in unprecedented detail. Intriguingly, images from these missions revealed thousands of distant background galaxies beyond the capability to study with onboard spectrometers. Probing the types and relative abundances of constituent elements and molecular gases of background galaxies, dating back to the first billion years of the universe, promises to unlock details of the cosmic origins and evolution of our universe.

Transition-edge sensors (TESs) remain a natural candidate for next-generation detectors on forthcoming cold (4 K), spaceborne spectrometers, where the inherent TES noise equivalent power (NEP) needs to fall below the NEP of background photons at the platform for realization of instrument potential. JPL-built TESs recently demonstrated NEP performance below the expected background photon levels for the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission (illustrated above), as part of the effort to build the JPL-designed Background-Limited Infrared Submillimeter Spectrograph (BLISS) instrument.



Above: The measured noise equivalent power (NEP) of the JPL TES operated at three resistances, R = 2.7, 1.57, and 0.64 $\mu\Omega$, in the resistive transition at 120 mK, demonstrating NEP $<10^{-19}$ W/Hz$^{1/2}$, which would allow background-limited performance on SPICA.

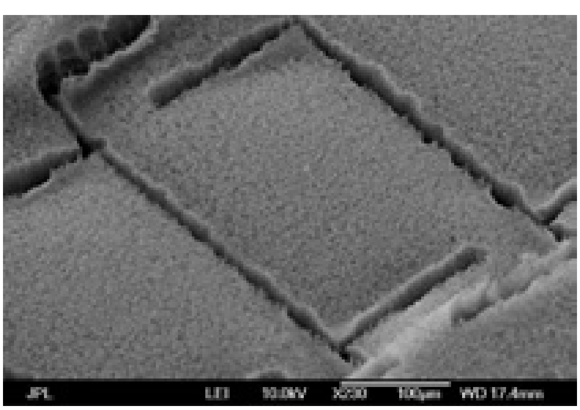




MDL Makes Significant Advancements in Development of State-of-the-Art Far-Infrared (FIR) Detector Arrays

In collaboration with Caltech, MDL fabricated and tested FIR prototype lumped element microwave kinetic inductance detector arrays, which are now photon-noise-limited for ground-based sites such as the Caltech Submillimeter Observatory. Characterization performed on 432-pixel prototype arrays and subsequent analysis including device yield, sensitivity, and noise performance has been used to design the next generation of focal plane arrays (FPAs). The new design includes simplification in the architecture of the sensors to improve yield and performance. We found that significant performance enhancement can be achieved by including optical focusing elements such as micro-lens arrays in front of the detector system. These improvements will be included in the next-generation FPAs to be produced in 2013.

Ultimately, larger arrays of ~2000 pixels per feedline will be fielded at the future submillimeter telescope, Cerro Chajnantor Atacama Telescope (CCAT). In the coming years we will also be developing higher sensitivity focal planes suitable for space-based FIR imagers for future NASA missions such as the Cryogenic Aperture Large Infrared Space Telescope Observatory (CALISTO) or the Single-Aperture Far-Infrared observatory (SAFIR).



Above: Measured noise equivalent power (NEP) spectrum of a representative pixel in dark blue. The red line is the computed photon noise expected at a ground-based telescope such as CSO or CCAT.

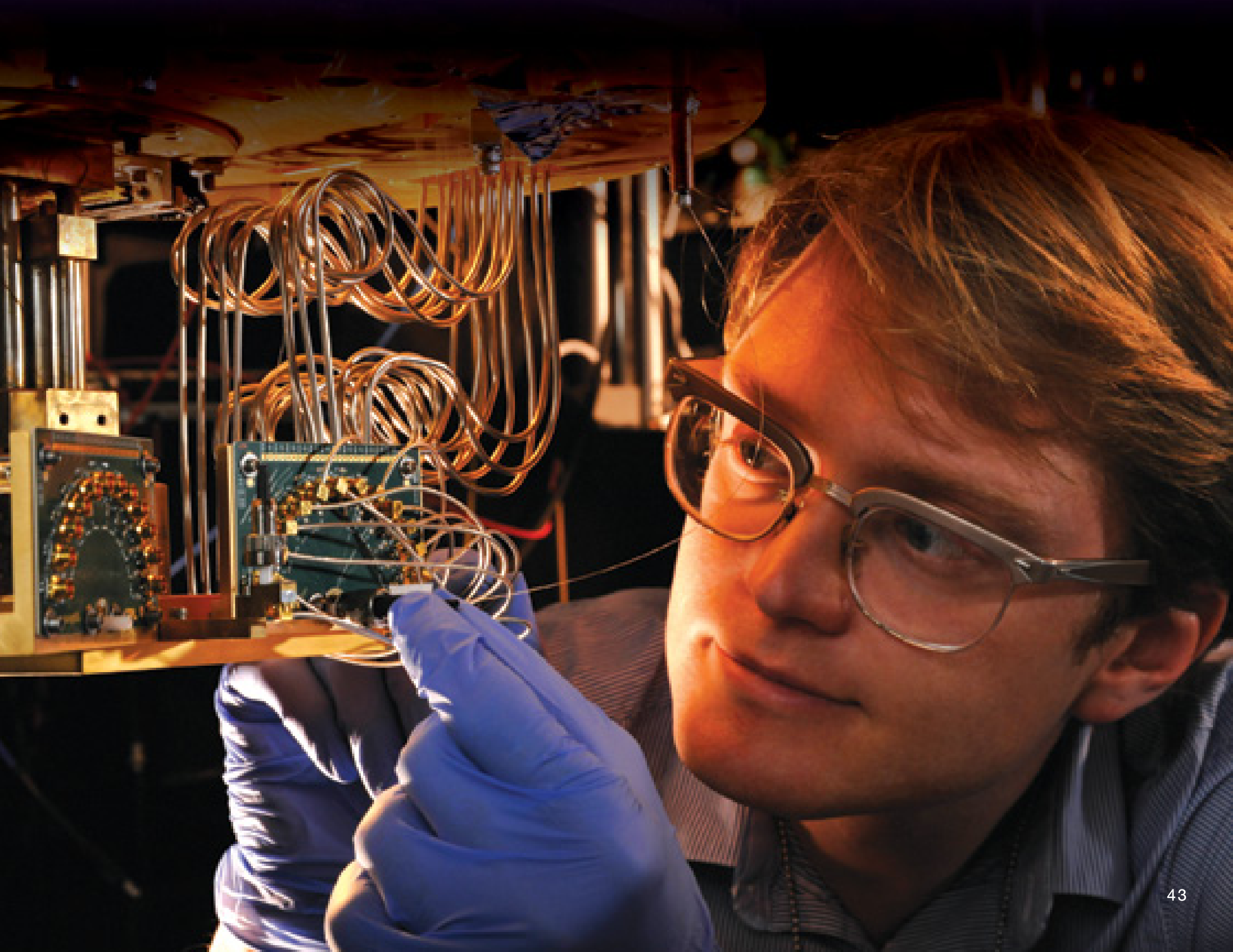
Thermopile Arrays for Space Applications

One of JPL's most important and successful product line instruments is the remote-sensing multisensing thermal imager (TI) using uncooled thermopile arrays. One TI is currently in orbit around Mars measuring the planet's atmosphere, and another TI is providing detailed thermal maps of the surface of our Moon. This year, 64x8–element thermopile arrays were fabricated at MDL, enabling an instrument like the Thermal Infrared Ganymede Radiometer Experiment (TIGRE), which was proposed this year for ESA's Jupiter Icy Moons Explorer (JUICE) mission to Jupiter. The measured sensitivity in terms of detectivity is D*>10^9 cm Hz$^{1/2}$/W, the response time is 70 ms, and the size of each pixel is 150 µm.

MDL's Tungsten Silicide Superconducting Nanowire Single-Photon Detector Development May Prove to Be Transformative Technology

Tungsten silicide (WSi) superconducting nanowire single-photon detector (SNSPD) arrays in the near-infrared have been under development at MDL under a NASA Office of the Chief Technologist (OCT) technology development program for deep-space optical communication. WSi SNSPDs offer single-photon sensitivity, near unit efficiency, subnanosecond timing resolution, tens of megahertz count rates per pixel, and very low false-count rates. In collaboration with NIST, we have developed WSi SNSPDs achieving a record-breaking 93% system detection efficiency at 1.55 microns with 140 ps timing jitter, a result recently published in *Nature Photonics*. We anticipate that this will be a transformative technology for a wide variety of applications that can benefit from time-correlated single-photon counting in the near infrared, such as optical communications, astrophysics, quantum communication and quantum optics, laser ranging and lidar, ultrafast spectroscopy, astrochemistry, and planetary science. MDL is currently developing 12-pixel fiber-coupled arrays for infusion into an optical communication technology demonstration, 64-pixel free-space coupled arrays of WSi SNSPDs for a proof-of-concept deep-space optical communication ground terminal, waveguide-coupled WSi SNSPDs for photonic integrated circuits, and large-format detector arrays for the DARPA "information in a photon" (InPho) program.

Below: A 12-pixel fiber-coupled tungsten silicide SNSPD array is prepared for measurement on a subkelvin refrigerator.



Below protective ice shells, Europa, Ganymede and Callisto are all thought to host internal oceans that may harbor life. ESA's Jupiter Icy Moons Explorer (JUICE) mission and NASA's Europa Clipper mission concept would use MDL-developed submillimeter spectrometers to assess these Jovian moons as potential habitats for life and to search for biosignatures such as methane (page 46).

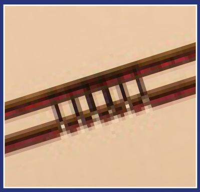
Artwork courtesy ESA/AOES.

SUBMILLIMETER-WAVE ADVANCED TECHNOLOGIES

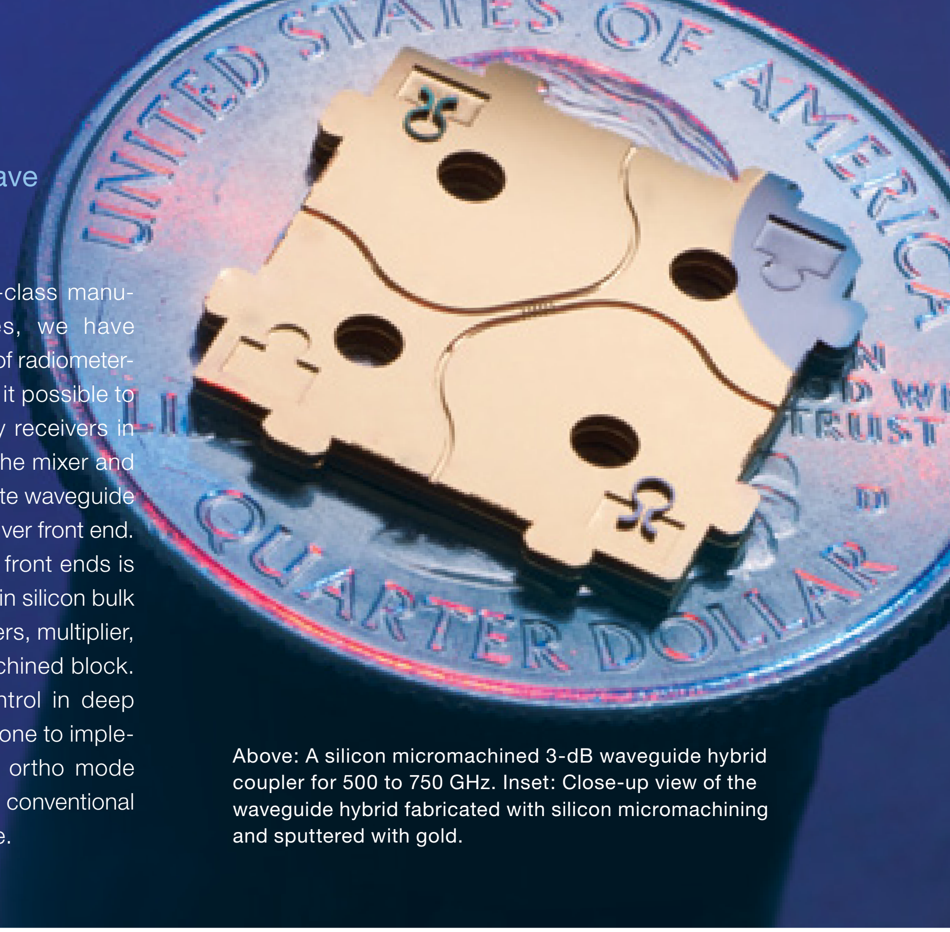
Our growing capabilities will allow us to peer into the early universe, keep us secure at airports and transit stations, and ensure exciting future missions to Venus and the outer planets.

One MDL specialty is developing and implementing submillimeter-wave and terahertz remote-sensing technologies for a variety of applications. A 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. MDL'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. >>

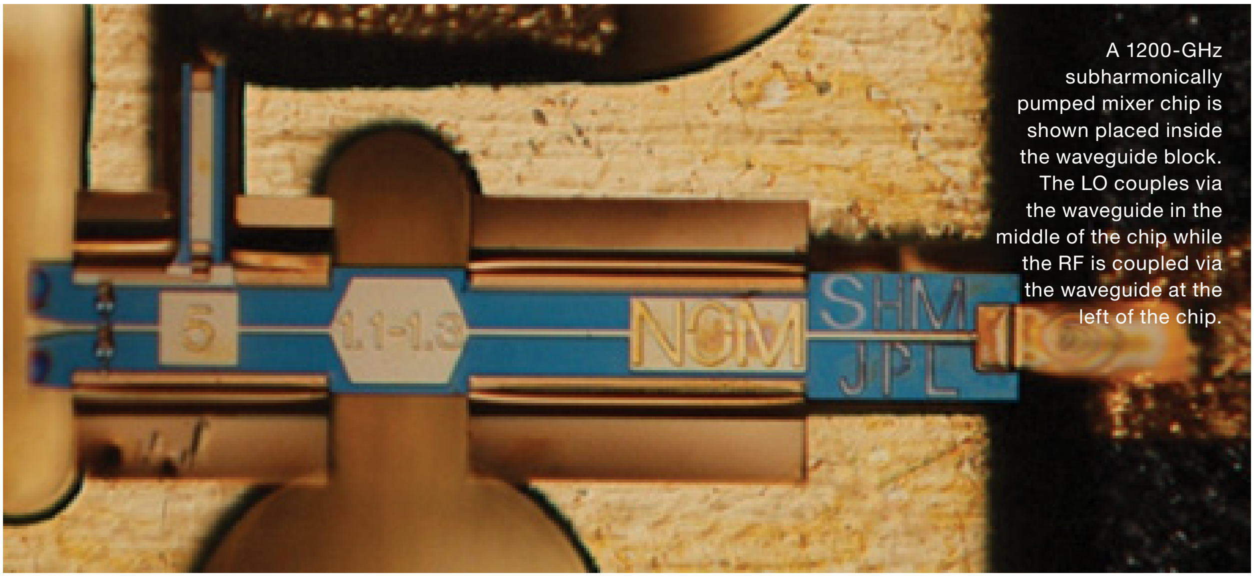
Ultra-Compact Submillimeter-Wave Receiver Components



Utilizing MDL's world-class manufacturing capabilities, we have developed a concept of radiometer-on-a-chip that makes it possible to deploy compact array receivers in the future. Normally, the mixer and the multiplier chips are packaged in separate waveguide blocks and then connected to form the receiver front end. One way to make super-compact receiver front ends is to etch the waveguide and channel cavities in silicon bulk material, and to integrate the power amplifiers, multiplier, and mixer chip in a single silicon micromachined block. Moreover, better feature dimensional control in deep reactive ion etching (DRIE) systems allows one to implement components such as couplers and ortho mode transducers that are difficult to implement in conventional machining in the terahertz frequency range.



Above: A silicon micromachined 3-dB waveguide hybrid coupler for 500 to 750 GHz. Inset: Close-up view of the waveguide hybrid fabricated with silicon micromachining and sputtered with gold.



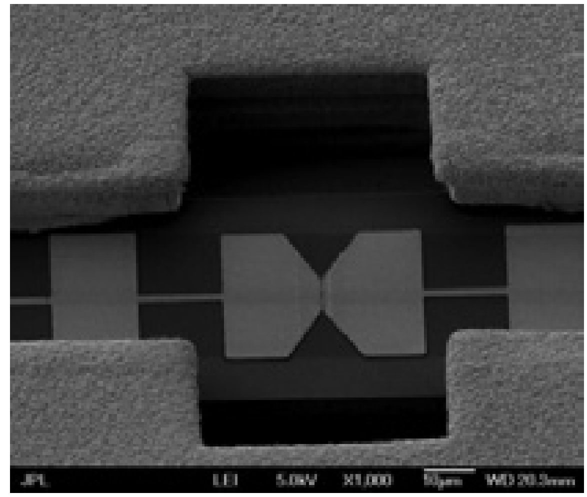
A 1200-GHz subharmonically pumped mixer chip is shown placed inside the waveguide block. The LO couples via the waveguide in the middle of the chip while the RF is coupled via the waveguide at the left of the chip.

MDL-Fabricated GaAs Planar Schottky Diodes Demonstrate Ability to Search for Methane on the Outer Planets

Detection of methane in the universe is a long-standing goal of NASA planetary missions. Advanced planar GaAs Schottky devices have been fabricated by MDL that can detect methane in planetary atmospheres with ppm sensitivities. Methane is an important signature for life sources and can allow scientists to focus on particular areas of a planet for detailed mapping. The upcoming ESA-sanctioned JUICE mission has included a submillimeter-wave instrument on the model payload. JPL is part of a European consortium that will build this instrument. A 1200-GHz receiver front end developed at MDL will enable the detection of methane at Jupiter.

Star-Forming Regions of the Universe Will Be Studied With Extremely Sensitive Heterodyne Front Ends Fabricated At MDL

Hot electron bolometer (HEB)–based mixers enable detection of very faint signals, making them a valuable tool for astrophysics research. Engineers at MDL have fabricated and designed HEB mixers that have been successfully deployed in receiver systems going up to 2.74 THz. Compact solid-state local oscillator (LO) sources have also been developed at these frequencies, enabling the deployment of compact receiver systems on platforms such as Stratospheric Observatory for Infrared Astronomy (SOFIA) and Galactic Ultra/Long Duration Balloon (U/LDB) for Spectroscopic/Stratospheric Terahertz Observatory (GUSSTO). The GUSSTO mission would launch a high-altitude balloon with a 1-meter telescope to provide a comprehensive understanding of the inner workings of our Milky Way galaxy including the formation of molecular clouds and star formation, and stellar evolution.



Above: A 1.9-THz HEB chip is shown placed inside the waveguide block.

THz Imaging Radar Allows for a Remote "Pat Down" in Hostile Environments

Schottky-diode-based mixer and multiplier devices have enabled us to build a 670-GHz imaging radar that can generate through-clothes imagery in around 1 second. A compact and robust instrument was built and delivered to the customer for field testing. The imaging rate of the instrument was increased by implementing several enhancements, including a new fast-scanning subreflector design, a faster but still low-noise chirp waveform generator, and faster analog-to-digital conversion and signal processing. Real-time through-clothes threat detection from 25-meter standoff ranges is now possible with frame rates of 1 Hz and spatial resolution of better than 1 cm. Work is under progress to enable multipixel imaging, thus further enhancing the imaging speed.

Right: The 670-GHz imaging radar system in operation.

Extreme-environment sensors and electronics are highly useful for commercial applications, including the oil and gas, automotive, and geothermal industries. MDL is developing advanced microdevices for prolonged operation in these harsh environments. The sensors will provide valuable scientific data that may help improve industrial processes, and in certain cases, avoid catastrophic damage.
Read more on page 50.

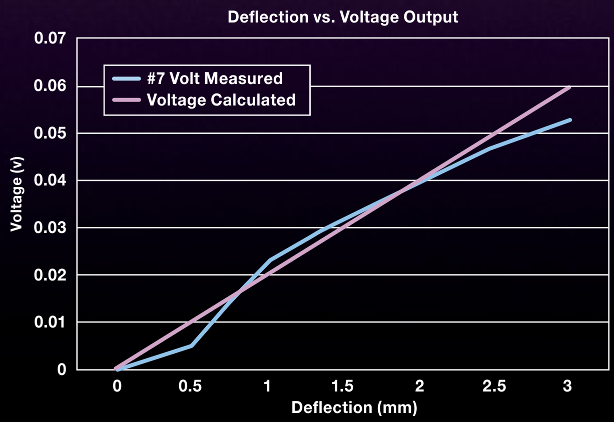
NANO AND MICRO SYSTEMS

Advances in nano and microtechnologies drive development of electronics and sensors in our everyday lives, Earth and planetary exploration, industry, and defense.

Nano and microtechnology efforts in the MDL focus on miniature system development activities for various customers, including NASA, DoD, and commercial entities. Development of the following technologies continues: advanced microgyroscopes, carbon nanotube and microsensor technologies for harsh-environment electronics, and advanced miniature tools for space exploration, as well as defense and commercial uses. >>

Microsensors for Space-Based and Terrestrial Harsh Environments

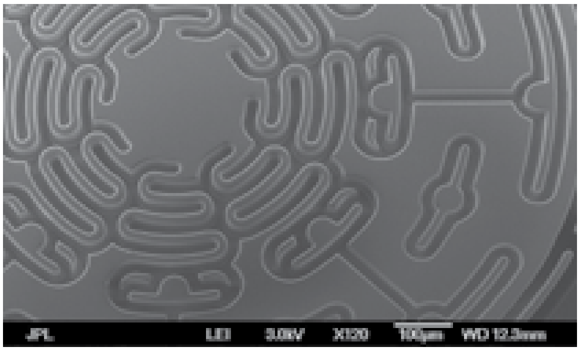
JPL is developing microsensors to monitor state variables, composition, and fluid flow that can provide valuable information regarding the ambient conditions of various harsh/extreme environments. On the surface of Venus, in the oil and gas production environment, and inside engines, such sensors help us to understand the operating environments, provide valuable scientific data, improve industrial processes, and in certain cases, avoid catastrophic damage. Due to the high temperature and extreme corrosiveness of these environments, the sensors require thermally tolerant, chemically resistant materials, and designs that can function reliably over a wide range of conditions. While just the sensors themselves are moderately challenging, the process of making them into packaged, integrated sensor systems with reliability, integration capability, and robustness to perform with high sensitivity over prolonged mission or application periods is extremely challenging on multiple levels. One type of MDL-fabricated ceramic flow sensor that can operate above 300 °C is pictured below.



Above left: Photograph of a ceramic flow sensor packaged for measurement electronics integration. Right: Calibration curve showing voltage change signal proportional to the flow-created deflection of the sensor. Below: Delivering science instruments through sulfuric acid clouds to land on the hostile surface of Venus at 460 °C and 92 times the atmospheric pressure of Earth will require sensors and electronics capable of performing in extreme environments.

MEMS Inertial Sensor Technology

JPL's silicon disc resonator gyroscope (Si DRG) is currently being commercialized and, through independent Army testing, has proven to be the highest performing microelectromechanical systems (MEMS) gyroscope in the world. The next generation of this device, the silicon nested-ring gyroscope (Si NRG), will incorporate geometric refinements for noise floor reduction and will utilize a JPL-developed wafer-scale vacuum packaging technology for decreased susceptibility to environmental changes, increased robustness, and greatly reduced cost. Research is being conducted on construction of resonant vibratory MEMS devices out of fused silica and ultra-low-expansion (ULE) glass for increased sensitivity; current work includes construction of planar and 3D micromachined gyroscopes and a 10 mm^3 inertial measurement unit for DARPA, and an RTD-funded fused silica, high-quality factor seismometer.



Above: Part of JPL's 10-cubic-millimeter timing and inertial measurement unit.

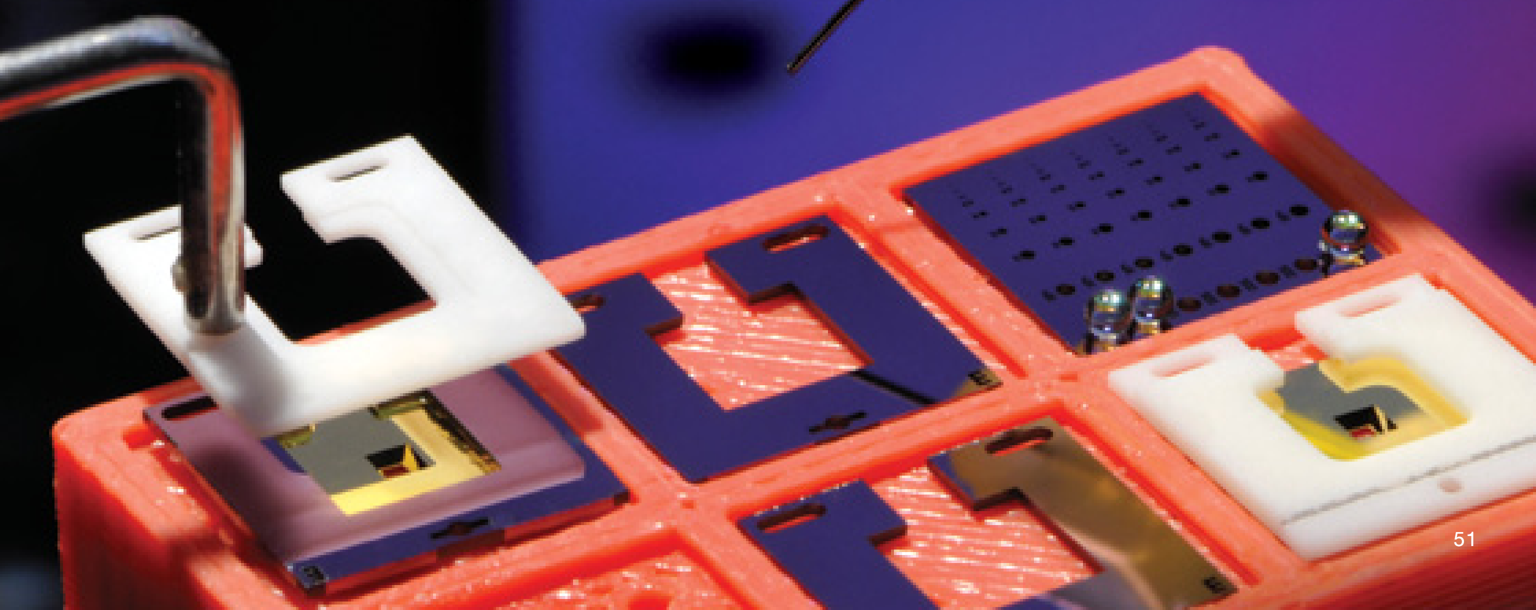
High-Temperature CNT Electronics

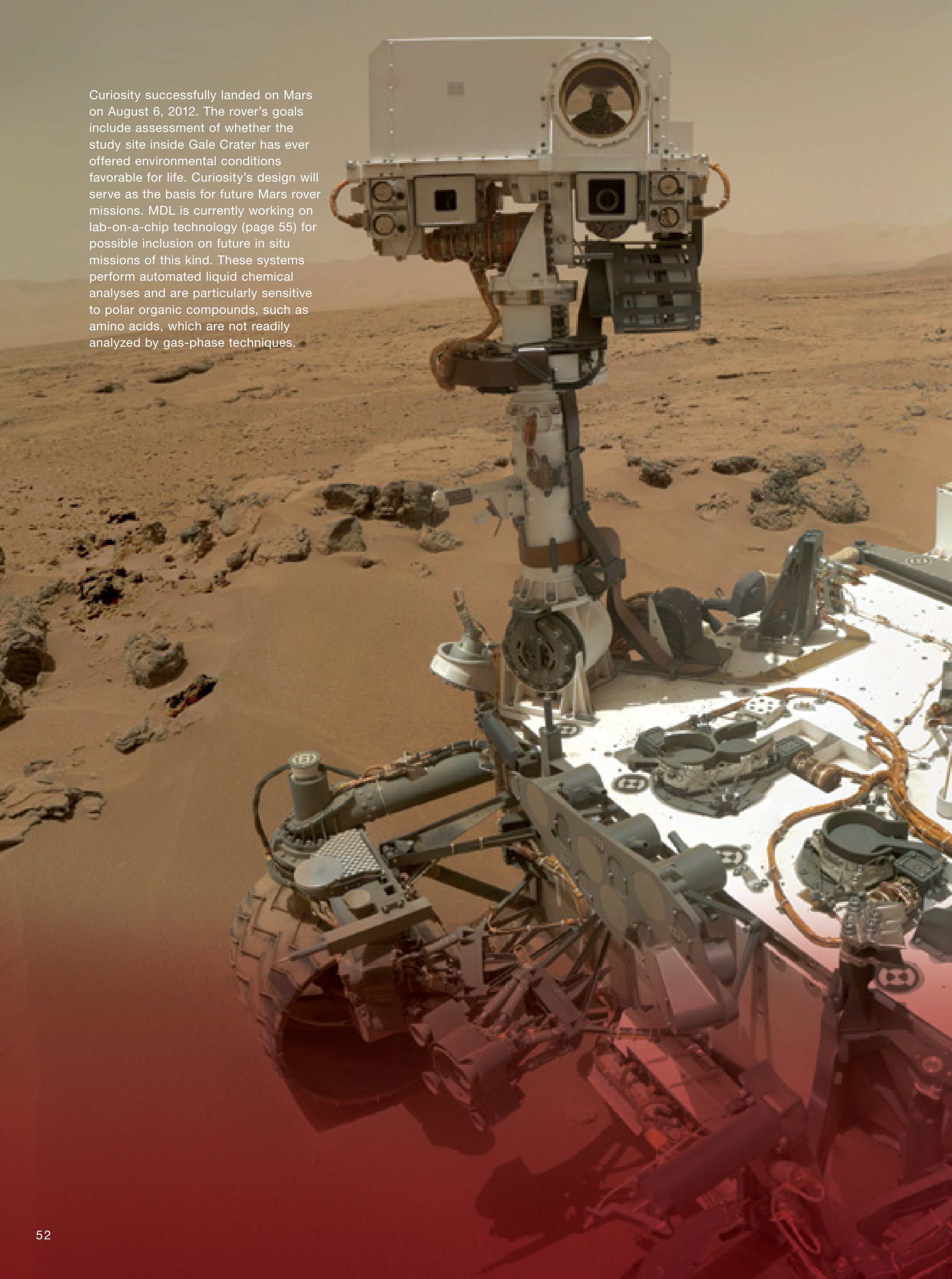
JPL has developed a new approach to high-temperature-tolerant electronic devices — both active and passive — using JPL's proprietary carbon nanotube (CNT) bundle array field emitters, silicon micromachining, hybrid micro-assembly, and improved vacuum packaging technologies. Since these devices make use of electron transport through vacuum instead of relying on semiconductor and metal contacts, they are inherently more high-temperature resistant and radiation insensitive.

To achieve high yield and repeatability, MDL has developed an advanced microassembly technique that enables hybrid assembly of different micromachined components with precision placement and alignment. These structures are then vacuum packaged at chip scale using a solder reflow bonding approach.

In addition, MDL has developed high-temperature-tolerant, small-scale capacitors, which utilize micromachined structures to obtain high-surface-area capacitor electrodes and advanced dielectric materials to yield high-temperature operation. They have been tested up to 1000 hours at 200 °C with less than 0.5 % degradation. These robust active devices and passive devices meet the needs of multiple harsh-environment space-based and terrestrial applications.

Below: A hybrid CNT vacuum electronic device ready for vacuum packaging. The device is made using a microassembly process involving metal-welded CNT cathodes, grid electrodes, and metallic anodes with precision spacers inside a ceramic sandwich.





Curiosity successfully landed on Mars on August 6, 2012. The rover's goals include assessment of whether the study site inside Gale Crater has ever offered environmental conditions favorable for life. Curiosity's design will serve as the basis for future Mars rover missions. MDL is currently working on lab-on-a-chip technology (page 55) for possible inclusion on future in situ missions of this kind. These systems perform automated liquid chemical analyses and are particularly sensitive to polar organic compounds, such as amino acids, which are not readily analyzed by gas-phase techniques.

MICROFLUIDICS

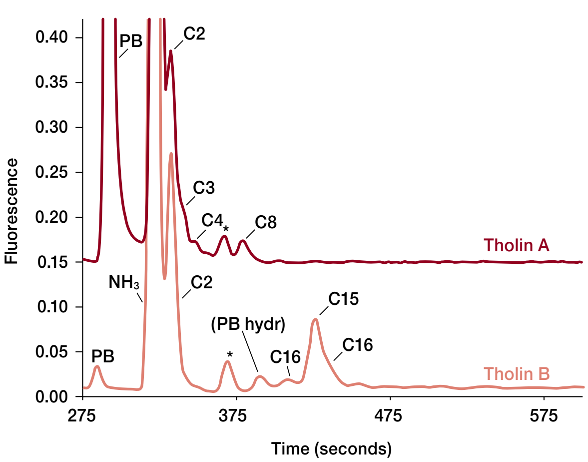
Lab-on-a-chip innovations capable of analyzing complex organics will integrate our natural and technological world through liquid-based technologies of the future.

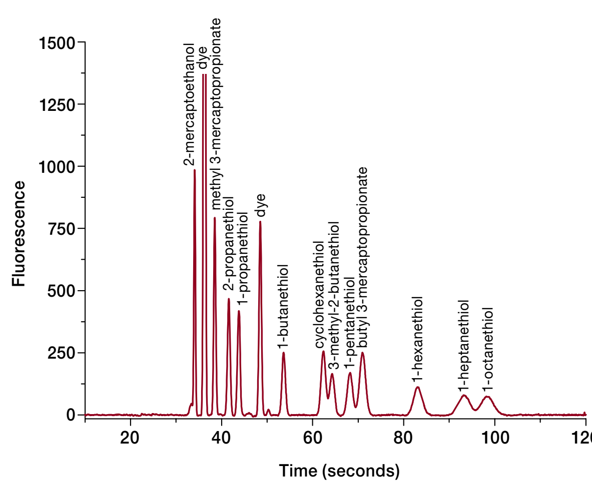
As planetary science evolved from the successful observational missions of the 70s, 80s, and 90s, there has been increased emphasis on the surface exploration of nearby accessible planets, resulting in the development and deployment of new physical, chemical, and geological instruments on robotic platforms. The work at MDL is focused on the development of the next generation of miniaturized lab-on-a-chip systems that can perform chemical analyses without needing a human operator during the process. Such technology is essential to NASA's search for habitable environments, prebiotic chemical syntheses, and extraterrestrial life in the solar system. >>


Nikon

Ultrasensitive Detection of Organic Compounds

Our analytical chemistry technique uses capillary electrophoresis coupled to laser-induced fluorescence detection for ultrasensitive detection of organic compounds in samples of astrobiological interest. This method first requires the use of a fluorescent dye that reacts with the compounds of interest so that they are visible to the technique. This past year, we have expanded the repertoire of chemical targets to include thiols, sulfur-bearing species of relevance to a broad range of planetary and biological phenomena. We have also developed methods to store and reconstitute the dyes we need for our technique and have determined conditions to preserve their useful lifetime on-chip. Finally, we have also performed a thorough optimization of the methods we use to pump fluids from place to place in the circuits we design in our four-layer microchip devices. This system optimization informs us on the design of future generations of microchip devices for efficient, contamination-free liquid transfer on other worlds. Our most ambitious, near-term NASA goal would be to include this technology on the payload of a 2020 rover to Mars, and to also implement this system on the International Space Station for environmental monitoring and general purpose chemistry analysis.





Left: Microchip electrophoresis data acquired from the analysis of Titan aerosol simulant samples (tholins) containing aliphatic amine compounds having different numbers of carbon atoms. Analyses take minutes to perform and can ascertain different “fingerprints” representative of chemical processes that formed the material. Right: Data acquired on a standard sample of thiol (sulfur)–containing compounds using a microchip method developed in MDL. Top of page: Photograph of a geothermal pool in Hot Creek, California, containing thiol compounds. Samples were collected from this pool and analyzed using these newly developed analytical methods.

The U.S. Space Launch System (SLS) will be the most powerful rocket in history and is designed to be flexible and evolvable, to meet a variety of crew and cargo mission needs. One such need is the exploration of asteroids. In support, MDL is developing microfluidic electrospray propulsion (page 58). The technology is compact enough that it could potentially enable small exploratory vehicles carried alongside, but not interfering with, the main payload on an SLS rocket. It is also powerful enough that it could be diverted from the main payload for an autonomous expedition, such as scouting future planetary or asteroid missions.

ADVANCED MICROFABRICATION TECHNOLOGIES

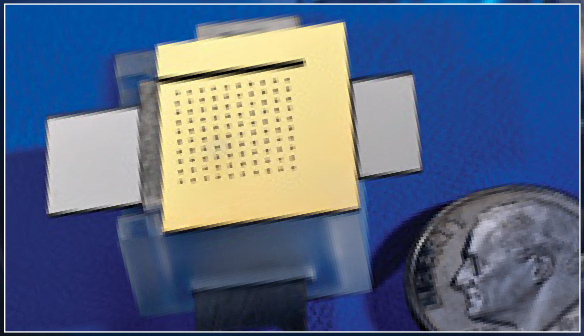
Microfabrication technologies under development at MDL continue to support NASA's mission to drive advances in science, technology, and exploration.

The performance requirements of JPL flight instruments have surpassed the ability of traditional microfabrication techniques. Using the state-of-the-art fabrication tools at MDL, engineers are developing new techniques to fabricate the next generation of components that will bring new capabilities to instruments. One result that utilizes these fabrication techniques would be the MDL silicon nitride membrane slit combined with black silicon. This critical component has revolutionized the performance of JPL imaging spectrometers. Another example, the 3D microfabrication technique, also developed at MDL, has enabled the fabrication of super-efficient ion engines to a point where it now can be considered a viable technology to propel a microspacecraft on an interplanetary mission. >>

Microfluidic Electrospray Propulsion Development for Small Spacecraft Missions

Small spacecraft currently under development in the 3- to 50-kilogram mass range have limited capabilities for propulsion and often rely on passive drift. Microfluidic electrospray propulsion (MEP) technology is under development at MDL to enable microspacecraft a velocity change in thousands of meters/second, which would enable them to propel to other planets and asteroids.

MEP is an electrospray thruster that uses a silicon chip etched with an array of micron-scale electrospray needles configurations fabricated at MDL with submicron precision. This capillary-force-driven feed system is microfabricated into the emitter array chip. The MEP assembly also includes a microfabricated heater chip, an extraction electrode chip plus an emitter array, and extraction grid chips microfabricated at the University of California, Irvine. MEP's feed system has no pressurized reservoir or valves. Its propellant (indium metal) is stored as a solid and then heated to melt and flow. It is then capillary-force-driven from a reservoir through the emitter array chip to the tip of the emitters, where high electric fields applied between the emitters and the extractor electrode extract and accelerate indium charged particles to create thrust. MEP is currently under development for 20 to 100 micronewtons of thrust. The thrust level is scalable with a number of emitters in the array. MEP will enable a velocity change of thousands of meters per second on small spacecraft and precision pointing of large spacecraft.



Above: A prototype MEP assembly using parts fabricated at both MDL and the University of California, Irvine. This highly integrated thruster and feed system assembly has a dry mass less than 10 grams.

This page: A prototype ion thruster being attached to a miniature satellite. MDL recently proposed ion drive microspacecraft sized no bigger than a shoe-box, but capable of flying themselves from just beyond Earth's Moon to Mars or the asteroid belt.

3D-Printed Micro-Parts for Ion Thrusters

Rapid prototyping is typically thought of as "3D printing," where a part is "printed out" from a CAD file in a way very analogous to how a computer generates a printed page from a PDF file, the difference being that a rapid prototyping machine generates a near-arbitrary 3D shape, instead of a 2D pattern on a piece of paper. Typically, objects printed from rapid-prototype machines are macro-objects, comparable to the size of a computer's mouse, with resolution that might be a few hundred pixels per inch laterally, and maybe 1/64th of an inch vertically.

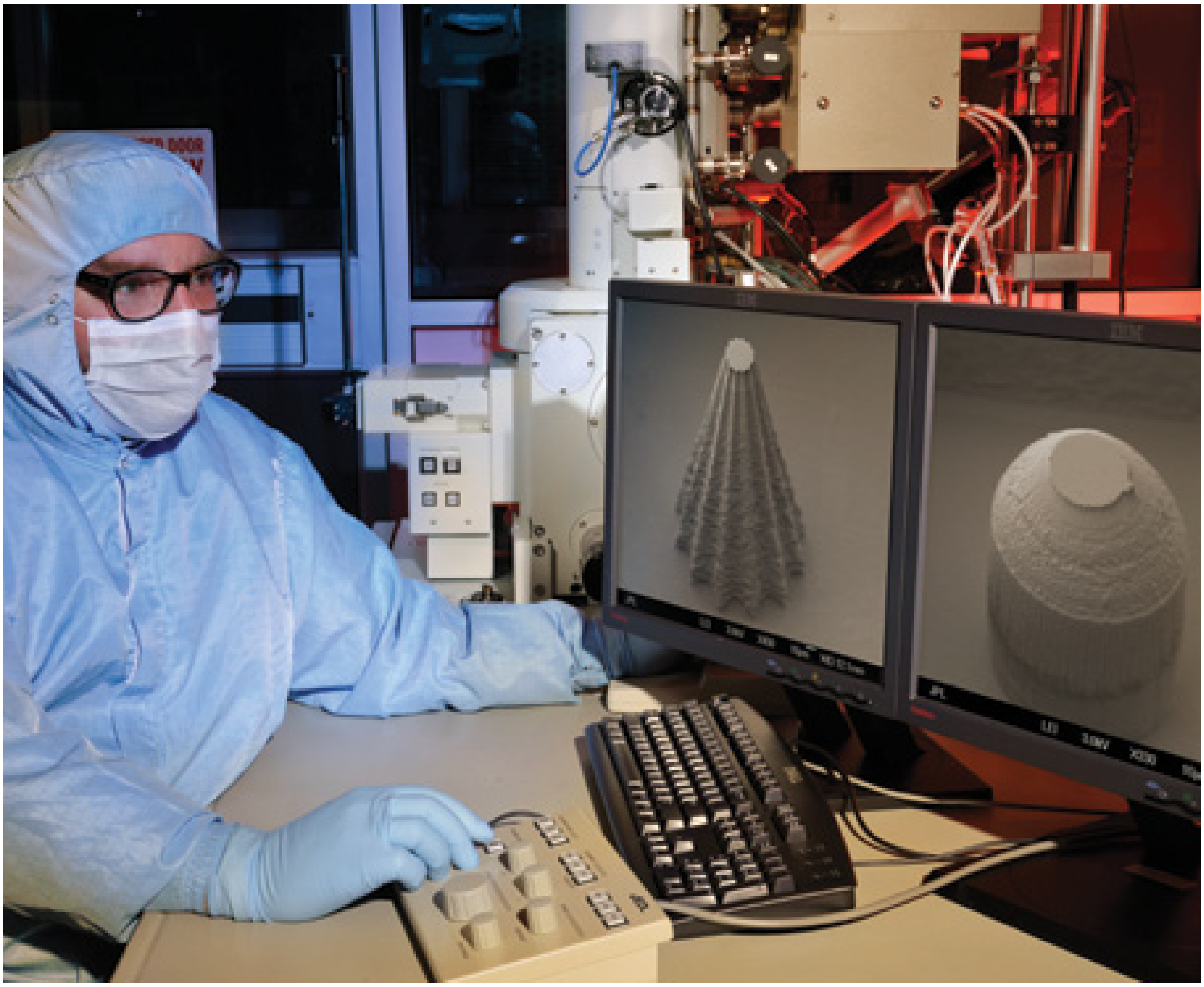
Researchers at MDL are working on replicating a gray-scale 3D pattern written into a thin layer of photoresist into a much deeper material where we preserve the morphology of the very thin 3D pattern. In effect, the very thin 3D pattern is "stretched" into a different and more mechanically useful material.

This technique borrows heavily from work at MDL where a 3D pattern is created in a thin photoresist layer using an electron-beam lithography machine to create a 2D pattern in a polymer, where the thickness of the remaining polymer depends entirely on the energy absorbed at any point on the photoresist.

Through a very careful optimized etch process, this pattern can be transferred into a material like silicon, which could be used directly for a device, or adapted as a mold to cast many more devices.

A major advantage of this process is that a CAD file describing a near-arbitrarily shaped 2D pattern with arbitrary thicknesses can be printed out with the e-beam lithography machine and "stretched" deep into another material, such as silicon.

Below: Sample test structures demonstrating the capabilities of 3D rapid prototyping. Structures are about 1/3 of a millimeter tall.



The ability to maintain cutting-edge research, development, and delivery of devices and technologies requires a sustained renewal and expansion of capabilities. In 2012, in alignment with long-range plans, MDL not only invested in multiple equipment upgrades, it also enlarged its processing area footprint by upgrading two Class 100,000 characterization labs into a Class 100 lithography area with service space to house two newly acquired steppers.

INFRASTRUCTURE

The foundation of our technical implementation and innovation relies on sophisticated new instrumentation in ultraclean, safe environments.

The sophisticated semiconductor processing that takes place in the MDL requires complex integrated building systems. Oversight and local configuration control is provided and there is also a small staff of processing personnel for specialized processing support. Management, coordination, and provision of direct services maintains the building infrastructure and equipment, including life safety systems for safety assurance. >>

Investment and Infrastructure Improvements

In MDL's continuing saga of growth and renewal, five important infrastructure improvements were made in 2012:

1. MDL's cleanroom processing area footprint was enlarged by upgrading two ISO 8 (Class 100,000) characterization labs into an ISO 5 (Class 100) lithography area with service space to house newly acquired steppers. This is in alignment with the master plan/vision for MDL developed in 2000, which allows processing area growth by converting characterization labs on the first floor into cleanroom processing areas and service spaces and moving the displaced characterization labs into the MDL annex constructed in 2004.

2. MDL's aging 350-kW emergency generator was replaced with an upgraded 500-kW unit to provide emergency power for life safety systems as well as providing additional power for critical systems in MDL.

3. A service bypass to a secondary chiller was installed for the cooling water on MDL's closed-loop process cooling water system. This will allow servicing to be done with a minimum of impacts to operations as well as providing for an emergency backup capability. This is consistent with MDL's charter of maintaining safe operations with a minimum of downtime.

4. Digital VoIP (Voice Over Internet Protocol) phones were added to MDL's labs and offices (replacing the majority of land lines). A custom linkage was provided to the local emergency annunciation system in the building. A few land lines were retained for emergency communication if the Internet system were to fail.

5. MDL's DI/RO water plant was redesigned and upgraded to improve water conservation, conserve electricity, and reduce maintenance. Savings of approximately 6 million gallons of water per year are projected.

In addition, in 2012 there were a large number of major equipment investments / upgrades for the following capabilities:

Lithography

Canon FPA3000 EX6 Deep Ultra Violet (DUV) Stepper Projection Mask Aligner: A DUV (248-nm) krypton fluoride laser source noncontact projection mask aligner

Above: A sample is loaded into the new Beneq TFS-200 atomic layer deposition (ALD) system.

with 150-nm resolution. It provides enhanced MDL optical lithography capabilities (improving resolution from 250 nm to 150 nm; overlay accuracy from 650 nm to 250 nm; distortion from 30 nm to 12 nm; and aberration from 9.3 nm to 2.5 nm) supporting the larger arrays and precision patternings necessary for thermopile arrays for future cold outer planet missions; for superconductor detector arrays for astrophysics (ground, balloon, satellite), optical communications, and quantum computer circuits; and for single-photon detectors for optical communications.

Canon FPA3000 i4 i-Line Stepper Projection Mask Aligner: An updated i-line (365 nm) noncontact projection mask aligner for MDL that upgrades MDL capabilities and resolution from 0.70 microns to 0.35 microns in the i-line resist family. It supports detector fabrications of Schottky diodes for high-frequency (hundreds of GHz to THz) applications, and patternings for long-wavelength infrared focal plane arrays (FPAs).

Deposition

Beneq TFS-200 Atomic Layer Deposition (ALD) System: Provides for enhanced and expanded capabilities in the area of atomic layer deposition, which enables the conformal chemical vapor deposition of precision dielectric and metal coatings a monolayer at a time.

Sample Preparation

Precitech Nanoform 250 Ultra Diamond Point Turning System (Task Specific vs. General Use): A single-point ultra-precision diamond turning machining system that provides the ability to thin and planarize bulk wafers in preparation for flip-chip bump bonding of infrared FPAs to readout electronics.

SET North America Ontos 7 Native Oxide (Indium Oxide) Removal Tool: Provides a very localized reducing atmosphere through an atmospheric plasma to remove the oxide from a metal surface, while it passivates with nitrogen molecules. It will be applied primarily to the removal of indium oxide from arrays of indium bumps in the flip-chip bump bonding process.

New Wave Research EzLaze 3 Laser Cutting System: A laser-trimming system integrated with an optical microscope to enhance detector reliability. It will enable the surface micromachining of polymers, metals and dielectrics to eliminate defects and shorts and trim thin-film resistors; as well as provide capabilities to micromachine photoresist to expose buried layers or for spot lithography for repairs. Feature sizes as small as 2 microns x 2 microns can be patterned.

Idonus HF VPE-150 Hydrofluoric Acid Vapor Phase Etcher: Allows for the atmospheric etching of silicon dioxide on silicon wafers and pieces utilizing hydrogen fluoride (HF) vapors instead of HF liquid, virtually eliminating fracturing in fragile microdevice fabricated structures.

SurfX 400L Atmospheric Surface Preparation System: Provides a reducing environment for surfaces by an atmospheric plasma that activates a surface for enhanced bonding applications.

Characterization

Horiba UVISEL 2 Ellipsometer System: Provides automated ellipsometry characterization of thin films from the deep ultraviolet (DUV) to the near-infrared (NIR) (190–2100 nm) spectral range with eight achromatic spot sizes (35 microns x 85 microns to 705 microns x 2030 microns) and an on-axis imaging system to allow precise beam positioning on patterned or nonuniform samples.

Measurement stand (FS10) and computer upgrade for FISBA μPhase 2 HR Compact Optical Interferometer: Enhances the MDL capability to measure the precision of optical surfaces. It is utilized to measure wafer flatness for infrared FPAs and to measure the topography of diffractive optic gratings.

Packaging

SCS Labcoter 2 (PDS 2010) Parylene Coating System (Task Specific vs. General Use): Allows for the deposition of ultra-thin conformal Parylene polymer coatings as a protective layer for components in extreme-environments applications.

Public Outreach

Significant participation in outreach activities was accomplished in 2012 with 12,321 members of the public physically accessing the MDL facility at the JPL Open House (June 9–10, 2012), and with more than nine MDL tours per month given during the year. "Signature chips" with over 1.2 million names and signatures from 246 countries around the world on ~1,300 pages miniaturized and written by MDL's e-beam lithography were packaged and mounted on the Mars Science Laboratory rover Curiosity in 2011 and delivered successfully to the surface of Mars in August 2012.

Appendix A — MDL Equipment Complement

Material Deposition

- Thermal Evaporators (6)
- Electron-Beam Evaporators (7)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Dielectrics and Metals (3)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Superconducting Materials (2)
- 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
- Low-Pressure Chemical Vapor Deposition (LPCVD) (Tystars) with 6 Tubes for
  - Low Stress Silicon Nitride (2)
  - Low Temperature Oxide – Silicon Dioxide
  - Doped and Undoped Polysilicon
  - Wet Pyrogenic Oxidation
  - Steam Oxidation
- Carbon Nanotube Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  - Veeco GEN200 (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

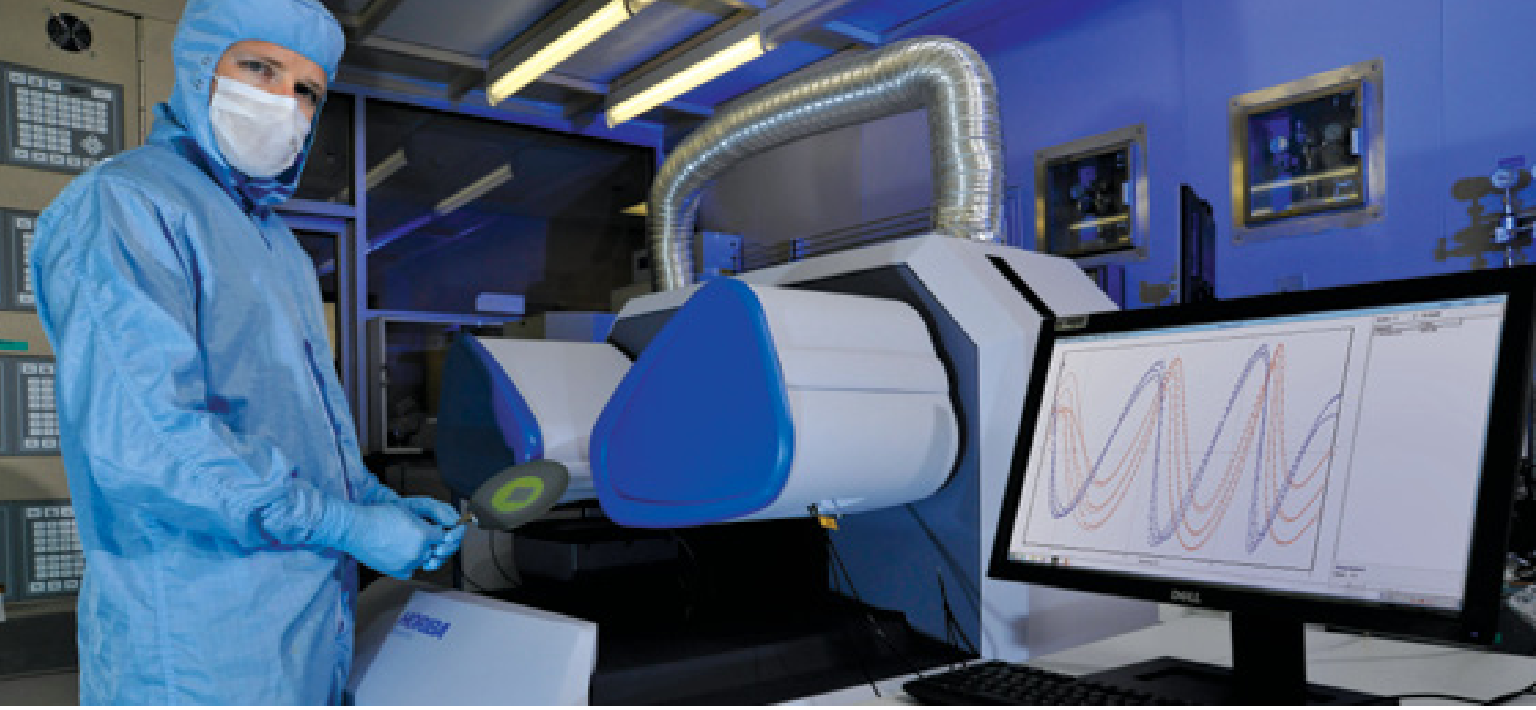
- Electron-Beam (E-beam) Lithography: JEOL JBX9300FS E-beam lithography system with a 4-nm spot size, 100,000-volt acceleration voltage, ability to handle wafers up to 12 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 7 mm of sag
- GCA Mann Wafer Stepper with custom stage allowing different sizes and thicknesses of wafers (0.7-µm resolution)
- Canon FPA3000 i4 i-Line Stepper (0.35-µm resolution)
- Canon FPA3000 EX3 Stepper with EX4 Optics (0.25-µm resolution)
- Canon FPA3000 EX6 DUV Stepper (0.15-µm resolution)
- Contact Aligners:
  - Karl Suss MJB3
  - Karl Suss MJB3 with backside IR
  - Suss MA-6 (UV300)
  - 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
- Yield Engineering System (YES) Reversal Oven
- Ovens, Hotplates, and Manual Spinners

Dry Etching

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

Fluorine-based Plasma Etching Systems

- STS Deep Trench Reactive Ion Etcher (DRIE) with SOI Upgrade
- Unaxis Shuttleline Load-Locked Fluorine ICP RIE



- 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 ICP RIE
- Plasmaster RME-1200 Chlorine RIE
- ECR 770 Chlorine RIE
- Oxford Inductively Coupled Plasma (ICP) Chlorine RIE

Wet Etching and Sample Preparation

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (7)
- Rinser/Dryers for Masks and Wafers
- 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
- Fynetech 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 Labcoter 2 (PDS 2010) Parylene Coating System

Characterization

- Profilometers (2)
- FSM 128 Film Stress Measuring system
- FISBA μPhase 2 HR Compact Optical Interferometer
- Senetech SE 850 Multispectral Ellipsometer
- Horiba UVISEL 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 EDS
- 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

Above: A thin film is characterized on the new Horiba UVISEL 2 (190–2100 nm) Ellipsometer.

Journal Publications

1. K. Chen, D. Cunnane, Y. Shen, X. X. Xi, A. W. Kleinsasser, and J. M. Rowell, "Multiple Andreev Reflection in MgB(2)/MgO/MgB(2) Josephson Junctions," *Appl. Phys. Lett.,* 100, 122601 (2012).

2. A. W. Kleinsasser, T. Chui, B. Bumble, and E. G. Ladizinsky, "Critical Current Density and Temperature Dependence of Nb-Al Oxide-Nb Junction Resistance and Implications for Room Temperature Characterization," *IEEE Trans. Appl. Supercond.,* 23, 3, 1100405 (2013).

3. F. Marsili, V. B. Verma, J. A. Stern, S. Harrington, A. E. Lita, T. Gerrits, I. Vasyshenker, B. Baek, M. D. Shaw, R. P. Mirin and S. W. Nam, "Detecting Single Infrared Photons with 93% System Efficiency," *Nature Photonics,* 7, pp. 210–214 (2013).

4. F. Boussaha, J. Kawamura, J. Stern, A. Skalare, V. White, and I. Mehdi, "A Low-Noise 2.7 THz Waveguide-Based NbN HEB Mixer," *IEEE Trans. on Terahertz Sci. and Tech.,* 2, 3 (April 2012).

5. B. Eom, P. Day, H. LeDuc, and J. Zmuidzinas, "A Wideband, Low-Noise Superconducting Amplifier with High Dynamic Range." *Nature Physics,* 8, pp. 623–627 (2012).

6. D. Moore, S. Golwala, B. Bumble, B. Cornell, P. Day, H. LeDuc, and J. Zmuidzinas, "Position and Energy-Resolved Particle Detection Using Phonon-Mediated Microwave Kinetic Inductance Detectors," *App. Phys. Lett.,* 100, 232601 (2012).

7. K. Stone, K. Megerian, P. Day, P. Echternach, J. Bueno, and N. Llombart, "Real-Time Quasiparticle Tunneling Measurements on an Illuminated Quantum Capacitance Detector," *App. Phys. Lett.,* 100, 263509 (2012).

8. O. Noroozian, P. Day, B. Eom, H. Leduc, and J. Zmuidzinas, "Crosstalk Reduction for Superconducting Microwave Resonator Arrays," *IEEE Trans. on Microwave Theory and Techniques,* 60, pp. 1235–1243 (2012).

9. A. Beyer, M. Kenyon, P. Echternach, T. Chui, B. Eom, P. Day, J. Bock, W. Holmes, and C. Bradford, "Ultra-Sensitive Transition-Edge Sensors for the Background Limited Infrared/Sub-mm Spectrograph (BLISS)," *J. Low Temperature Phys.,* 1, 6 (2012).

10. M. Faverzani, P. Day, A. Nucciotti, E. Ferri, "Developments of Microresonators Detectors for Neutrino Physics in Milan," *J. Low Temp. Phys.,* 1, 7 (2012).

11. D. Moore, S. Golwala, B. Bumble, B. Cornell, B. Mazin, J. Gao, P. Day, H. LeDuc, and J. Zmuidzinas, "Phonon Mediated Microwave Kinetic Inductance Detectors," *J. Low Temp. Phys.,* 1, 6 (2012).

12. A. Trebi-Ollennu, K. S. Ali, A. L. Rankin, K. S. Tso, C. Assad, J. B. Matthews, R. G. Deen, D. A. Alexander, R. Toda, H. Manohara, M. Mojarradi, M. Wolf, J. R. Wright, J. Yen, F. Hartman, R. G. Bonitz, A. R. Sirota and L. Alkalai, "Lunar Surface Operation Testbed (LSOT)," *IEEE Aerospace 2012*.

13. S. Y. Bae, R. Korniski, J. Choi, P. Barhami, H. Manohara, and H. Shahinian, "Development of a Miniature Single Lens Dual-Aperture Stereo Imaging System Towards Stereo Endoscopic Imaging Application," *Optical Eng.,* 51, 10, 103202-1 (2012).

14. S. Y. Bae, R. Korniski, A. Ream, H. Shahinian, and H. Manohara, "A New Technique of 3D Imaging Through a 3-mm Single Lens Camera," *Optical Eng.,* 51, 2, 021106 (2012).

15. M. Shearn, S. Y. Bae, R. Korniski, H. Manohara, J. Mondry, and H. Shahinian, "Multi-Angle Rear-Viewing Endoscopic Tool (MARVEL) for Minimally Invasive Neurosurgeries," *J. Medical Devices,* 6, 1, 017540-1 (2012).

16. V. J. Scott, M. Tse, M. J. Shearn, P. H. Siegel, and X. Amashukeli, "An RF-Powered Micro-Reactor for the Detection of Astrobiological Target Molecules on Planetary Bodies," *Rev. Sci. Inst.,* 83, 084102 (2012).

17. V. J. Scott, P. H. Siegel, and X. Amashukeli, "Controlled Hydrolysis of Lysozyme with an RF-Powered Micro-Reactor," *Anal. Meth.,* accepted (2012).

18. M. F. Mora, A. M. Stockton, and P. A. Willis, "Analysis of Thiols by Microchip Capillary Electrophoresis for In Situ Planetary Investigations," *Electrophoresis,* 34, pp. 1–8 (2012).

19. M. F. Mora, A. M. Stockton, and P. A. Willis, "Microchip Capillary Electrophoresis Instrumentation for In Situ Analysis in the Search for Extraterrestrial Life," *Electrophoresis,* 33, pp. 2624–2638 (2012).

20. M. L. Cable, S. M. Hörst, R. Hodyss, P. M. Beauchamp, M. A. Smith, and P. A. Willis, "Titan Tholins: Simulating Titan Organic Chemistry in the Cassini–Huygens Era," *Chem. Rev.,* 112, pp. 1882–1909 (2012).

21. R. M. Briggs, C. Frez, M. Bagheri, C. E. Borgentun, J. A. Gupta, M. F. Witinski, J. G. Anderson, and S. Forouhar, "Single-Mode 2.65 μm InGaAsSb/AlInGaAsSb Laterally Coupled Distributed-Feedback Diode Lasers for Atmospheric Gas Detection," *Opt. Exp.,* 21, pp. 1317–1323 (2013).

22. S. Forouhar, R. M. Briggs, C. Frez, K. J. Franz, and A. Ksendzov, "High-Power Laterally Coupled

Distributed-Feedback GaSb-Based Diode Lasers at 2 µm Wavelength," *App. Phys. Lett.,* 100, 031107 (2012).

23. A. Ksendzov, S. Forouhar, R. M. Briggs, C. Frez, K. J. Franz, and M. Bagheri, "Linewidth Measurement of High-Power Diode Laser at 2 Micrometers for Carbon Dioxide Detection," *Electron. Lett.,* 48, pp. 520–522 (2012).

24. S. B. Rafol, A. Soibel, A. Khoshakhlagh, J. Nguyen, J. K. Liu, J. M. Mumolo, S. A. Keo, L. Hoglund, D. Z. Ting, and S. D. Gunapala, "Performance of a ¼ VGA Format Long-Wavelength Infrared Antimonide-Based Superlattice Focal Plane Array," *IEEE J. Quant. Electron.,* 48, 7, pp. 878–884 (2012).

25. J. Nguyen, A. Soibel, S. B. Rafol, A. Khoshakhlagh, J. K. Liu, J. M. Mumolo, L. Hoglund, S. A. Keo, D. Z. Ting, and S. D. Gunapala, "Inductively Coupled Plasma Etching of Complementary Barrier Infrared Detector Focal Plane Arrays for Long-Wave Infrared Imaging," *IEEE Photon. Technol. Lett.,* 24, 18, pp. 1581–1583 (2012).

26. W. R. Johnson, S. J. Hook, and S. M. Shoen, "Microbolometer Imaging Spectrometer," *Opt. Lett.,* 37, pp. 803–805 (2012).

27. S. Nikzad, M. E. Hoenk, F. Greer, B. Jacquot, S. Monacos, T. J. Jones, J.Blacksberg, E. Hamden, D. Schiminovich, C. Martin, and P. Morrissey, "Delta-Doped Electron-Multiplied CCD with Absolute Quantum Efficiency Over 50% in the Near to Far Ultraviolet Range for Single Photon Counting Applications," *App. Opt.,* 51, 124508 (2012).

28. B. C. Jacquot, M. E. Hoenk, T. Jones, T. J. Cunningham, and S. Nikzad, "Direct Detection of 1000–5000 eV Electrons with Delta Doped Silicon CMOS and Electron-Multiplying CCD Imagers," *IEEE Trans. on Electron Devices,* 59, 7, pp. 1988–1992 (2012).

29. F. Greer, E. Hamden, B. C. Jacquot, M. E. Hoenk, T. Jones, M. Dickie, S. P. Monacos, and S. Nikzad, "Atomically Precise Surface Engineering of Silicon CCDs for Enhanced UV Quantum Efficiency," *J. of Vac. Sci. Technol.,* A 01A103-1 (2013).

Conference Proceedings and Publications

1. R. O'Brient, P. Ade, Z. Ahmed, R. Aikin, M. Amiri, S. Benton, C. Bischo, J. Bock, J. Bonetti, J. Brevik, et al., "Antenna-Coupled TES Bolometers for the Keck Array, Spider, and Polar-1," *Proc. of SPIE,* Vol. 8452, 84521G (2012).

2. E. Shirokoff, P. Barry, C. Bradford, G. Chattopadhyay, P. Day, S. Doyle, S. Hailey-Dunsheath, M. Hollister, A. Kovacs, C. McKenney, et al., "MKID Development for Super-Spec: An On-Chip, Millimeter-Wave, Filter-Bank Spectrometer," *SPIE Astronomical Telescopes + Instrumentation,* 84520R (2012).

3. L. Swenson, P. Day, C. Dowell, B. Eom, M. Hollister, R. Jarnot, A. Kovacs, H. Leduc, C. McKenney, R. Monroe, et al., "MAKO: A Pathfinder Instrument for On-Sky Demonstration of Low-Cost 350 Micron Imaging Arrays," *SPIE Astronomical Telescopes + Instrumentation,* 84520P (2012).

4. A. D. Beyer, P. M. Echternach, M. E. Kenyon, M. C. Runyan, B. Bumble, C. M. Bradford, J. J. Bock, and W. A. Holmes, "Effect of Mo/Cu Superconducting Bilayer Geometry on Ultra-Sensitive Transition-Edge Sensor Performance," *IEEE Trans. App. Supercond.,* 23, 3, 2100104 (June 2013).

5. A. D. Beyer, M. E. Kenyon, P. M. Echternach, B. A. Bumble, M. C. Runyan, T. C. Chui, C. M. Bradford, W. A. Holmes, and James J. Bock, "Development of Fast, Background-Limited Transition-Edge Sensors for the Background-Limited Infrared/Sub-mm Spectrograph (BLISS) for SPICA," Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI, Wayne S. Holland; Jonas Zmuidzinas, Editors, *Proc. SPIE*, Vol. 8452 (SPIE, Bellingham, WA 2012), 84520G.

6. C. M. Bradford, A. D. Beyer, M. E. Kenyon, M. Runyan, B. A. Bumble, P. M. Echternach, T. Prouve, W. A. Holmes, J. J. Bock, and K. Irwin, "Progress Toward BLISS, the Background-Limited Infrared–Submillimeter Spectrograph for SPICA," Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave, Mark C. Clampin; Giovanni G. Fazio; Howard A. MacEwen; Jacobus M. Oschmann, Jr., Editors, *Proc. SPIE,* Vol. 8442 (SPIE, Bellingham, WA 2012), 84420P.

7. Y. Maruyama, J. Blacksberg, and E. Charbon, "A Time-Resolved 128x128 SPAD Camera for Laser Raman Spectroscopy," *Proc. SPIE*, Vol. 8374, 83740N (2012).

8. A. Soibel, J. Nguyen, S. B. Rafol, A. Liao, L. Hoeglund, A. Khoshakhlagh, S. A. Keo, J. M. Mumolo, J. Liu, D. Z. Ting, and S. D. Gunapala, "High-Performance LWIR Superlattice Detectors and FPA Based on CBIRD Design," *Proc. SPIE*, Vol. 8268, 82680Y (2012).

9. S. D. Gunapala, D. Z. Ting, S. B. Rafol, A. Soibel, J. K. Liu, A. Khoshakhlagh, S. A. Keo, J. M. Mumolo, and J. Nguyen, "Performance of Antimonide Based Small Format Infrared Focal Plane Arrays," *Proc. of 2012 Meeting of the Military Sensing Symposium, Joint Session Materials/Detectors,* Paper DMC06 (March 2012).

10. D. Z. Ting, A. Soibel, A. Khoshakhlagh, S. A. Keo, S. B. Rafol, J. K. Liu, J. M. Mumolo, and S. D. Gunapala, "High Operating Temperature Barrier Infrared Detectors," *Proc. of the 2012 Meeting of the Military Sensing Symposium, Joint Session Materials/Detectors,* Paper DMA01, invited (March 2012).

11. A. Soibel, J. Nguyen, A. Khoshakhlagh, S. B. Rafol, L. Hoeglund, S. A. Keo, J.M. Mumolo, J. Liu, A. Liao, D. Z.-Y. Ting, and S. D. Gunapala, "High-Performance LWIR Superlattice Detectors and FPA Based on CBIRD Design," *Proc. SPIE*, Vol. 8353, 83530U (2012).

12. J. Nguyen, S. B. Rafol, A. Soibel, A. Khoskhlagh, D. Z.-Y. Ting, J. K. Liu, J. M. Mumolo, and S. D. Gunapala, "320 x 256 Complementary Barrier Infrared Detector Focal Plane Array for Long-wave Infrared Imaging," *Proc. SPIE*, Vol. 8353, 835331 (2012).

13. D. Z. Ting, A. Soibel, C. J. Hill, Sam A. Keo, J. M. Mumolo, and S. D. Gunapala, "High Operating Temperature Midwave Quantum Dot Barrier Infrared Detector (QD-BIRD)," *Proc. SPIE*, Vol. 8353, 835332 (2012).

14. F. Greer, L. Baker, S. Cook, A. Fisher, S. Keo, A. Soibel, A. Khoshakhlagh, J. Nguyen, D. Ting, and S. Gunapala, "Fundamental Interface Studies of GaSb and InAs Substrates with Atomic Layer Deposition," *Proc. SPIE*, Vol. 8511, 8511-8 (2012).

15. S. B. Rafol, S. D. Gunapala, D. Z. Ting, A. Soibel, A. Khoshakhlagh, J. Nguyen, L. Höglund, J. K. Liu, J. M. Mumolo, S. A. Keo, and E. M. Luong, "Characterization of Type II SLS n-CBIRD Focal Plane Array," *Proc. SPIE*, Vol. 8511, 8511-7 (2012).

16. L. Höglund, A. Soibel, D. Z. Ting, A. Khoshakhlagh, C. J. Hill, and S. D. Gunapala, "Minority Carrier Lifetime and Photoluminescence Studies of Antimony-Based Superlattices," *Proc. SPIE*, Vol. 8511, 8511-6 (2012).

17. D. Z. Ting, S. A. Keo, J. K. Liu, J. M. Mumolo, A. Khoshakhlagh, A. Soibel, J. Nguyen, L. Höglund, S. B. Rafol, C. J. Hill, and S. D. Gunapala, "Barrier Infrared Detector Research at the Jet Propulsion Laboratory," *Proc. SPIE*, Vol. 8511, 8511-4, invited (2012).

18. J. Nguyen, J. Gill, S. B. Rafol, A. Soibel, A. Khoskhlagh, D. Ting, S. Keo, A. Fisher, E. Luong, J. Liu, J. Mumolo, and S. D. Gunapala, "Inductively Coupled Plasma Etching for Delineation of InAs/GaSb Pixels," *Proc. SPIE*, Vol. 8511, 8511-3 (2012).

19. A. Soibel, E. Luong, J. M. Mumolo, J. Liu, S. B. Rafol, S. A. Keo, W. Johnson, D. Willson, C. J. Hill, D. Z.-Y. Ting, and S. D. Gunapala, "Multi-Color QWIP FPAs for Hyperspectral Thermal Emission Instruments," *Proc. SPIE*, Vol. 8511, 8511-5 (2012).

20. Arezou Khoshakhlagh, D. Z. Ting, L. Höglund, A. Soibel, S. B. Rafol, J. Nguyen, S. A. Keo, J. Mumolo, J. Liu, and S. D. Gunapala, "Type-II InAs/GaSb Superlattice Detectors Based on CBIRD Design," *Proc. SPIE*, Vol. 8512, 8512-0I (2012).

21. W. R. Johnson, S. J. Hook, M. Foote, B. T. Eng, and B. Jau, "Infrared Instrument Support for HyspIRI-TIR," *Proc. SPIE*, Vol. 8511, Infrared Remote Sensing and Instrumentation XX, 851102 (2012).

22. D. R. Thompson, W. R. Johnson, and R. L. Kremens, "Multiple-Frame Subpixel Wildfire Tracking," *IEEE Geosci. and Remote Sens. Lett.,* 9, pp. 639–643 (2012).

23. B. Cornell, D. Moore, S. Golwala, B. Bumble, P. Day, H. LeDuc, and J. Zmuidzinas, "High-Resolution Gamma-Ray Detection Using Phonon-Mediated Detectors," *Proc. SPIE*, Vol. 84532, *Astronomical Telescopes + Instrumentation,* 84532N (2012).

24. C. McKenney, H. LeDuc, L. Swenson, P. Day, B. Eom, and J. Zmuidzinas, "Design Considerations for a Background-Limited 350-Micron Pixel Array Using Lumped Element Superconducting Microresonators," *Proc. SPIE*, Vol. 84520, *Astronomical Telescopes + Instrumentation,* 84520S (2012).

25. M. Bagheri, R. M. Briggs, C. Frez, A. Ksendzov, and S. Forouhar, "Narrow-Linewidth Distributed Feedback Semiconductor Lasers Operating at 2 μm," 23rd International Semiconductor Laser Conference (ISLC 2012), San Diego, CA (October 2012).

26. R. M. Briggs, C. Frez, A. Ksendzov, K. J. Franz, and S. Forouhar, "Laterally Coupled Distributed-Feedback GaSb-Based Diode Lasers for Atmospheric Gas Detection at 2 μm," Conference on Lasers and Electro-Optics (CLEO), San Jose, CA (May 2012).

27. S. Forouhar, R. M. Briggs, C. Frez, M. Bagheri, and J. A. Gupta, "Record High-Power Laterally Coupled Distributed-Feedback Lasers in the 2–3 μm Wavelength Range," 11th International Conference on Infrared Optoelectronics: Materials and Devices (MIOMD-XI), Chicago, IL (September 2012).

28. R. M. Briggs, C. Frez, M. Bagheri, K. J. Franz, R. D. May, and S. Forouhar, "Carbon Monoxide Monitoring for Low-Power Spacecraft Fire Detection Systems Using Quantum Cascade Laser Sources at 4.6 μm," 11th International Conference on Infrared Optoelectronics: Materials and Devices (MIOMD-XI), Chicago, IL (September 2012).

29. E. T. Hamden, D. Schiminovich, S. Nikzad, and D. C. Martin, "UV Photon-Counting CCD Detectors That Enable the Next Generation of UV Spectroscopy Missions: AR Coatings That Can Achieve 80–90% QE," Paper 8453-8, *Proc. SPIE*, Vol. 8453 (2012).

30. S. Nikzad, M. Hoenk, F. Greer, S. Monacos, B. Jacquot, T. Jones, E. T. Hamden, D. Schiminovich, D. C. Martin, and P. Morrissey, "UV Photon Counting Detectors Enabling the Next Generation of UV Spectroscopy Missions," Paper 8453-10, *SPIE Astronomical Telescope and Instrumentation*, Amsterdam, Netherlands (July 2012).

31. T. Veach, P. A. Scowen, M. Beasley, and S. Nikzad, "Modified Modular Imaging System Designed for a Sounding Rocket Experiment," Paper 8446-285, *Proc. SPIE* 8446 (2012).

32. W. Traub, F. Greer, and S. Nikzad, "Mirror Coatings with Atomic Layer Deposition: Initial Results," Paper 8442-52, *Proc. SPIE*, Vol. 8442 (2012).

33. M. Beasley, F. Greer, S. Nikzad, "Progress in New Ultraviolet Reflective Coating Techniques," Paper 8443-136, *Proc. SPIE*, Vol. 8443 (2012).

34. I. Mehdi, "THz Imaging Radar Technology Development for Multi-Pixel Multi-Color Architectures," *IEEE MTT-S International Microwave Symposium Digest,* Montreal, Canada (June 2012).

35. G. Chattopadhyay, "Technology, Capabilities, and Performance of Low-Power THz Sources," *IEEE MTT-S International Microwave Symposium Digest,* Montreal, Canada (June 2012).

36. G. Chattopadhyay, "Silicon Micromachined Receiver Front-End at Terahertz Frequencies," *Proc. IEEE International Workshop on Antenna Technology,* Karlsruhe, Germany (March 2013).

37. M. Alonso, N. Llombart, G. Chattopadhyay, C. Lee, C. Jung-Kubiak, L. Jofre, and I. Mehdi, "Design Guidelines for a Terahertz Silicon Micro-Lens Antenna," *IEEE Ant. and Prop. Lett.,* AWPL-11-12-1440 (March 2013).

38. A. Y. Tang, E. Schlecht, R. Lin, G. Chattopadhyay, C. Lee, J. Gill, I. Mehdi, and J. Stake, "Electro-Thermal Model for Multi-Anode Schottky Diode Multipliers," *IEEE Trans. Terahertz Science and Technology,* Vol. 2, No. 3, pp. 290–298 (May 2012).

39. K. B. Cooper, N. Llombart, G. Chattopadhyay, R. Dengler, R. E. Cofield, C. Lee, S. Filchenkov, and E. Koposova, "A Grating-Based Circular Polarization Duplexer for Submillimeter-Wave Transceivers," *IEEE Microwave and Wireless Components Letters,* Vol. 22, No. 3, pp. 108–110 (March 2012).

40. A. Maestrini, I. Mehdi, J. Siles, J. S. Ward, R. Lin, B. Thomas, C. Lee, J. Gill, G. Chattopadhyay, E. Schlecht, J. Pearson, and P. H. Siegel, "Design and Characterization of a Room Temperature All-Solid-State Electronic Source Tunable from 2.48 to 2.75 THz," *IEEE Trans. Terahertz Science and Technology,* Vol. 2, No. 2, pp. 177–185 (March 2012).

41. G. Chattopadhyay, T. Reck, E. Schlecht, R. Lin, and W. Deal, "Cryogenic Amplifier Based Receivers at Submillimeter Wavelengths," *Proc. 37th International Conference on Infrared, Millimeter, and Terahertz Waves,* Wollongong, Australia (November 2012).

42. C. Lee, G. Chattopadhyay, K. Cooper, and I. Mehdi, "Curvature Control of Silicon Microlens for THz Dielectric Antenna," *Proc. 37th International Conference on Infrared, Millimeter, and Terahertz Waves,* Wollongong, Australia (November 2012).

43. J. Siles, G. Chattopadhyay, E. Schlecht, C. Lee, R. Lin, J. Gill. C. Jung, I. Mehdi, A. Maestrini, and P. H. Siegel, "Next Generation Solid-State Broadband Frequency-Multiplied Terahertz Sources," *Proc. IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting,* Chicago, IL (July 2012).

44. T. Reck, C. Jung-Kubiak, C. Lee, G. Chattopadhyay, N. Llombart, and I. Mehdi, "Terahertz Antenna Arrays," *Proc. IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting,* Chicago, IL (July 2012).

45. E. Shirokoff, P. Barry, C. M. Bradford, G. Chattopadhyay, P. Day, S. Doyle, S. Hailey-Dunsheath, A. Kovacs, C. McKenny, H. G. LeDuc, N. Llombart, D. P. Marrone, P. Mauskopf, R. O'Brient, S. Padin, L. Swenson, and J. Zmuidzinas, "SuperSpec: An On-Chip, Millimeter-Wave, Filter-Bank Spectrometer with MKID Readout," *Proc. SPIE Astronomical Telescopes and Instrumentation,* Amsterdam, Netherlands (July 2012).

46. I. Mehdi, J. Siles, R. Lin, G. Chattopadhyay, C. Lee, J. Gill, E. Schlecht, T. Reck, and C. Jung, "Local Oscillator Subsystems for Array Receivers in the 1–3 THz range," *Proc. SPIE Astronomical Telescopes and Instrumentation,* Amsterdam, Netherlands (July 2012).

47. C. Jung-Kubiak, J. Gill, T. Reck, C. Lee, J. Siles, G. Chattopadhyay, R. Lin, K. Cooper and I. Mehdi, "Silicon Microfabrication Technologies for THz Applications," *Proc. IEEE Silicon Nanoelectronics Workshop,* Honolulu, HI (June 2012).

48. T. Reck, J. Siles, C. Jung, J. Gill, C. Lee, G. Chattopadhyay, I. Mehdi, and K. B. Cooper, "Array Technology for Terahertz Imaging," *Proc. SPIE Defense, Security, and Sensing Conference,* Baltimore, MD (April 2012).

49. G. Chattopadhyay, P. Barry, C. M. Bradford, P. Day, S. Doyle, S. Hailey-Dunshath, A. Kovacs, H. G. LeDuc, N. Llombart, C. McKenny, D. P. Marrone, P. Mauskopf, R. O'Brient, S. Padin, T. Reck, E. Shirokoff, J. Siles, L. Swenson, and J. Zmuidzinas, “Ultra-Compact Superconducting Spectrometer on a Chip at Submillimeter Wavelengths,” *Proc. 23rd International Symposium on Space Terahertz Technology,* Tokyo, Japan (April 2012).

50. J. Siles, G. Chattopadhyay, A. Maestrini, R. Lin, C. Lee, C. Jung, J. Gill, A. Peralta, E. Schlecht, and I. Mehdi, “Enabling Compact Multi-Pixel Heterodyne Terahertz Receivers Using On-Chip Power-Combined Multiplied Sources,” *Proc. 23rd International Symposium on Space Terahertz Technology,* Tokyo, Japan (April 2012).

51. T. Reck, C. Jung, J. Siles, B. Thomas, J. Gill, J. Ward, R. Line, I. Mehdi, and G. Chattopadhyay, “PASEO — An Integrated Radiometer and Spectrometer for Improved Planetary Science,” *Proc. 23rd International Symposium on Space Terahertz Technology,* Tokyo, Japan (April 2012).

52. G. Chattopadhyay, N. Llombart, C. Lee, C. Jung, R. Lin, K. B. Cooper, T. Reck, J. Siles, E. Schlecht, A. Peralta, B. Thomas, and I. Mehdi, “Terahertz Array Receivers with Integrated Antennas,” *Proc. IEEE International Workshop on Antenna Technology: Small Antennas and Unconventional Applications,* Tucson, AZ (March 2012).

53. H. Manohara, “Miniaturization Technologies for Space Exploration and their Crossover Applications,” *MEMS Enabled Spacecraft Systems: AIAA-ASM 2012 Conference,* Nashville, TN.

54. H. Manohara, M. Mojarradi, R. Toda, and R. Lin, “Carbon Nanotube-Based High-Temperature Vacuum Microelectronics for E&P Applications,” *SPE International Oilfield Nanotechnology Conference and Exhibition,* Noordwijk, Netherlands (June 2012).

New Technology Reports

1. R. Toda, V. White, H. Manohara, K. Patterson, N. Yamamoto, E. Gdoutos, J. Steeves, C. Daraio, and S. Pellegrino, “Fabrication Methods for Adaptive Deformable Mirrors,” NTR #48665 (2012).

2. H. Manohara and M. Mojarradi, “Digital Vacuum Microelectronics for Harsh Environment Applications,” NTR #48617 (March 2012).

3. H. Manohara, M. Mojarradi, and L. Del Castillo, “Harsh Environment Microsensors and Deployment Schemes for Planetary Sub-Surface Diagnostics,” NTR #48623 (March 2012).

4. C. Frez, R. M. Briggs, S. Forouhar, and C. Borgentun of Caltech; and J. Gupta of the National Research Council, Canada, “High-Power, Single-Mode, 2.65-μm, InGaAsSb/AlInGaAsSb Diode Lasers,” NPO #48926.

5. C. Frez, R. M. Briggs, M. Bagheri, A. Ksendzov, and S. Forouhar, “High-Power Single-Mode GaSb-Based Diode Lasers at 2 μm for Remote Detection of Carbon Dioxide,” NPO #48769.

6. R. M. Briggs, C. Frez, and S. Forouhar, “Index-Coupled Distributed-Feedback Semiconductor Quantum Cascade Lasers Fabricated Without Epitaxial Regrowth,” NTR #49037 (2013).

7. F. Greer, S. Keo, D. Ting, A. Fisher, S. Gunapala, J. Nguyen, and A. Khoshakhlagh, “Interfacial Cleaning of LWIR Photodiodes Using ALD-based Passivation,” NPO #48610.

8. D. Ting, A. Khoshakhlagh, C. Hill, S. Keo, A. Soibel, and S. Gunapala, “Barrier Infrared Detectors on Alternative Substrates,” NPO #48955.

9. M. E. Hoenk, A. Carver, and S. Nikzad, “Sub-Bandgap Silicon Detector Fabrication Using Molecular Beam Epitaxy for Nanoscale Bandstructure Engineering,” NTR #48886.

10. M. E. Hoenk, S. Nikzad, and A. Carver, “Method and Device for Fully Depleted Particle Detectors Covering a Wide Energy Range,” NTR.

11. F. Greer, S. Nikzad, M. Lee, S. George, and M. Beasley, “Novel Chemistry for Deposition of MgF_2 Thin Films,” (U of Colorado) NTR.

Patents

1. H. M. Manohara, A. Liao, Y. Bae, and H. K. Shahinian, “Endoscope and System and Method of Operation Thereof,” December 4, 2012, US 8323182.

2. P. A. Willis, H. Jiao, F. Greer, A. M. Fisher, M. F. Mora, A. M. Stockton, and M. L. Cable, “The Chemical Laptop,” U.S. Provisional Patent filed September 24, 2012, CIT-5905-P.

3. C. Frez, R. M. Briggs, S. Forouhar, and C. Borgentun of Caltech; and J. Gupta of the National Research Council, Canada, “High-Power, Single-Mode, 2.65-μm, InGaAsSb/AlInGaAsSb Diode Lasers,” CIT patent filed.

4. D. Ting, A. Khoshakhlagh, A. Soibel, C. Hill, and S. Gunapala “Barrier Infrared Detectors,” U.S. Patent No. US 8,217,480 B2, July 10, 2012.

5. M. Hoenk, “Surface Passivation by Quantum Exclusion Using Multiple Layers,” U.S. Patent No. 8,395,243, issued March 12, 2013.

6. S. Nikzad, M. Hoenk, and C. Martin. “Advanced Low Voltage Safe Low Light Level Imager and Detector,” patent issued.

4. K. B. Cooper, R. J. Dengler, P. H. Siegel, G. Chattopadhyay, J. S. Ward, N. Llombart, T. E. Bryllert, I. Mehdi, and J. A. Tarsala, “Multi-Pixel High-Resolution Three-Dimensional Imaging Radar,” U.S. Patent No. US 8,144,052 B2.

5. M. M. Mojarradi, G. Chattopadhyay, H. Manohara, and H. Mojarradi, “Integrated Ultra Thin Scalable 94 GHz SI Power Source,” U.S. Patent No. US 8,193,995 B2.

Awards and Other Distinguished Recognition

1. Shouleh Nikzad was elected a fellow of the *American Physical Society* (APS).

2. Shouleh Nikzad was elected Senior Research Scientist (SRS) at JPL.

3. Shouleh Nikzad was selected as a role model by the *SPIE Women in Optics (WIO)* and featured in the SPIE WIO’s Mentoring and Recruiting Publication.

4. Shouleh Nikzad was invited to participate on a panel for future UV missions and instruments in the workshop *UV Astronomy, Hubble Space Telescope and Beyond*, Kuaui, HI, June 2012.

5. James Lamb (MDL Manager) was elected Senior Member of the American Institute of Aeronautics and Astronautics (AIAA).

6. Harish Manohara, Eric W. Wong, Erich T. Schlecht, Brian D. Hunt, and Peter H. Siegel received a NASA Patent Award for “Nanotube Schottky Diodes for High Frequency Applications.”

7. Risaku Toda, Michael J. Bronikowski, Edward M. Luong, and Harish Manohara received a NASA Patent Award for “A Carbon Nanotube Field Emission Device with Overhanging Gate.”

8. Harish Manohara and Michael J. Bronikowski received a NASA Patent Award for “Carbon Nanotube High-Current-Density Field Emitters.”

9. Sarath Gunapala served on the Steering Committee of the Mid Infrared Opto-Electronic Materials and Devices (MIOMD) 2012 Conference, Evanston, IL, Sept. 5–8, 2012.

10. Sarath Gunapala served on the Program Committee of the SPIE Infrared Technology and Applications XXXVIII Conference, Baltimore, MD, April 5–8, 2012.

11. S. D. Gunapala, S. B. Rafol, D. Z. Ting, A. Soibel, J. K. Liu, A. Khoshakhlagh, S. A. Keo, and J. M. Mumolo received a best paper award for “Modulation Transfer Function of Infrared Focal Plane Arrays” at the MIOMD 2012 Conference, Evanston, IL, Sept. 5–8, 2012.

12. Sarath Gunapala served on the Program Committees of the SPIE Infrared Remote Sensing and Instrumentation XX and SPIE Infrared Sensors, Devices, and Applications II Conferences, San Diego, CA, Aug. 10–15, 2012.

13. IEEE Photonics Society has selected Sarath Gunapala as an Associate Editor for the IEEE Photonics Journal. He also serves on their Technical Subcommittee on Photodetectors, Imaging, and EO Sensors.

14. April Jewell, a NASA Postdoctoral Program fellow, received two awards for her PhD work from the American Vacuum Society: The Morton M. Traum Surface Science Award and the Russell & Sigurd Varian Award.

15. Doug Bell initiated a new symposium for the Materials Research Society (MRS) 2013 Fall Meeting.

16. Hamid Javadi received a NASA Group Achievement Award for outstanding contributions leading to the successful development, delivery, and launch of the Juno Microwave Radiometer instrument.

17. Hamid Javadi received a JPL Team Award for the implementation of an RF electronics test program resulting in significant reduction in development risk.

18. Jose Siles received a 2012 JPL Outstanding Postdoctoral Research Award on Technology, Instrumentation, and Engineering for “Compact Power-Combined Multiplied Sources to Enable Terahertz Multi-Pixel Heterodyne Spectroscopy.”

19. Dr. Adrian Tang received a Distinguished Ph.D. Dissertation Award from the Henry Samuli School of Engineering, UCLA.

20. Dr. Adrian Tang was awarded First Place in the Broadcom Foundation University Research Competition.

21. Dr. Lorene Samoska et al. was a 2012 Research Poster Conference Award Winner for “MMIC Low Noise Amplifier Modules up to 700 GHz – A World Record Enabling Technology.”

22. “Compact Detectors for Submillimeter-Wave Spectrometers for JGO” was a 2012 JPL Research Poster Conference Award Winner by Dr. Sam Gulkis, Dr. Imran Mehdi, Dr. Jose V. Siles, Dr. Erich T. Schlecht, and Dr. Goutam Chattopadhyay.

JPL Microdevices Laboratory Visiting Committee

Above (left to right): Top row: George Komar, William Hunt, Oskar Painter, Jed Harrison, Gilbert Herrera, A. Fenner Milton, Robert Trew, and N. George Ugras. Bottom row: Gregory Kovacs, Eustace Dereniak, Regina Ragan, and Barbara Wilson.

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[1] Optical Society of America
[2] Institute of Electrical and Electronics Engineers
[3] American Association for the Advancement of Science
[4] American Institute for Medical and Biological Engineering
[5] American Physical Society

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