National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology

Microdevices Laboratory

LET'S WORK TOGETHER

2013 Annual Report

LET'S WORK TOGETHER

At the Microdevices Laboratory (MDL), we actively seek to partner with organizations throughout the world, including universities, private industry, and medical and other research institutions. We believe these collaborative efforts continue to bring remarkable achievements and innovations not only for NASA's space and Earth science programs, but also for national security, the advancement of technology, and the betterment of society. Visit us online at microdevices.jpl.nasa.gov

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Photograph by Denis Barkats.

WORKING TOGETHER TO UNRAVEL THE SECRETS OF THE BIRTH OF THE UNIVERSE

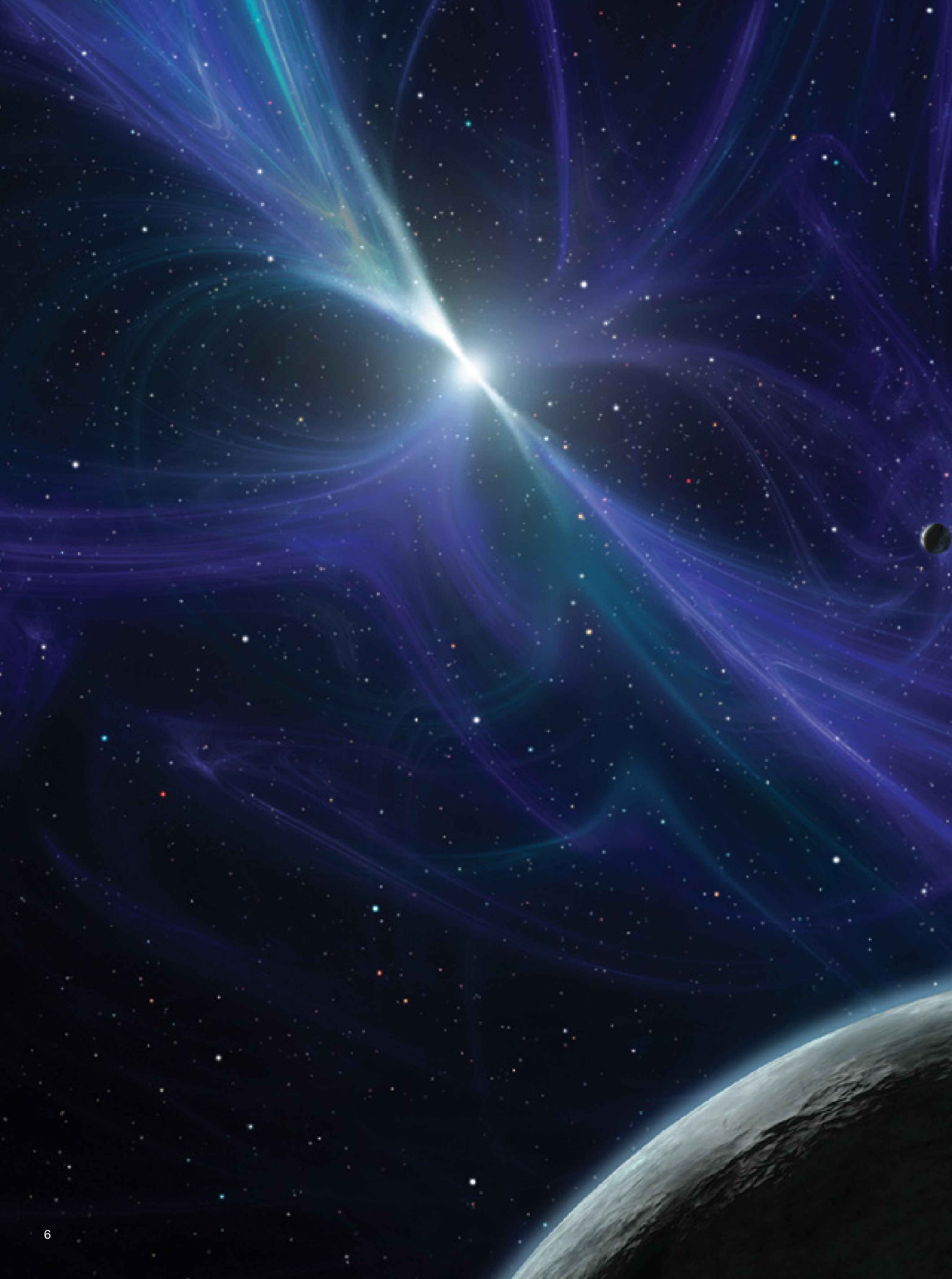
MDL devices on the BICEP2 telescope at the South Pole are helping scientists confirm key aspects of the theory of cosmic inflation.

On March 17, 2014, news outlets reported the ground-breaking discovery of direct evidence for cosmic inflation obtained from measurements of the polarization of the cosmic microwave background (CMB) radiation using the BICEP2 telescope at the South Pole. Cosmic inflation, a leading model of the early universe, includes the concept that the size of the universe expanded by some fifty orders of magnitude in a sudden episode only 10^{-35} seconds after the Big Bang. Inflation was predicted to produce a background of gravitational waves whose faint imprint is now being seen by BICEP2. For this observation, BICEP2 relied on a powerful new superconducting detector array technology developed at MDL. BICEP2 is the first of a new generation of instruments enabled by MDL technology spearheaded by the Caltech/JPL experimental cosmology group led by Caltech professor and JPL Senior Research Scientist Jamie Bock, along with collaborators at Harvard University, Stanford University, University of Minnesota, and other institutions.

WORKING TOGETHER TO MONITOR THE EFFECTS OF CLIMATE CHANGE

Anderson Research Group at Harvard University is developing tools with MDL to measure the effects of greenhouse gases on our atmosphere.

The East Siberian Arctic Shelf, a swath of land underneath the East Siberian Sea, is known to contain large frozen deposits of highly concentrated methane hydrates. When these hydrates melt, they release methane gas, a greenhouse gas 25 times more potent than carbon dioxide. Understanding how much methane is stored in the shelf and if those stores are stable is vital to climate research. The Anderson Research Group at Harvard is working on a number of projects that address global-scale issues relating to climate change such as this, specifically the rate and effects of a warming climate on our atmosphere. Achieving this goal will provide decision support for a range of societal issues, including water resources, human health, natural resources, energy management, and infrastructure. The group, under the leadership of James G. Anderson, has partnered with MDL to develop laser devices to aid their continuing research.



WORKING TOGETHER TO STUDY THE DENSEST KNOWN OBJECTS IN NATURE

MDL is collaborating with MIT to develop low-energy X-ray detectors that may help gather new information about neutron stars.

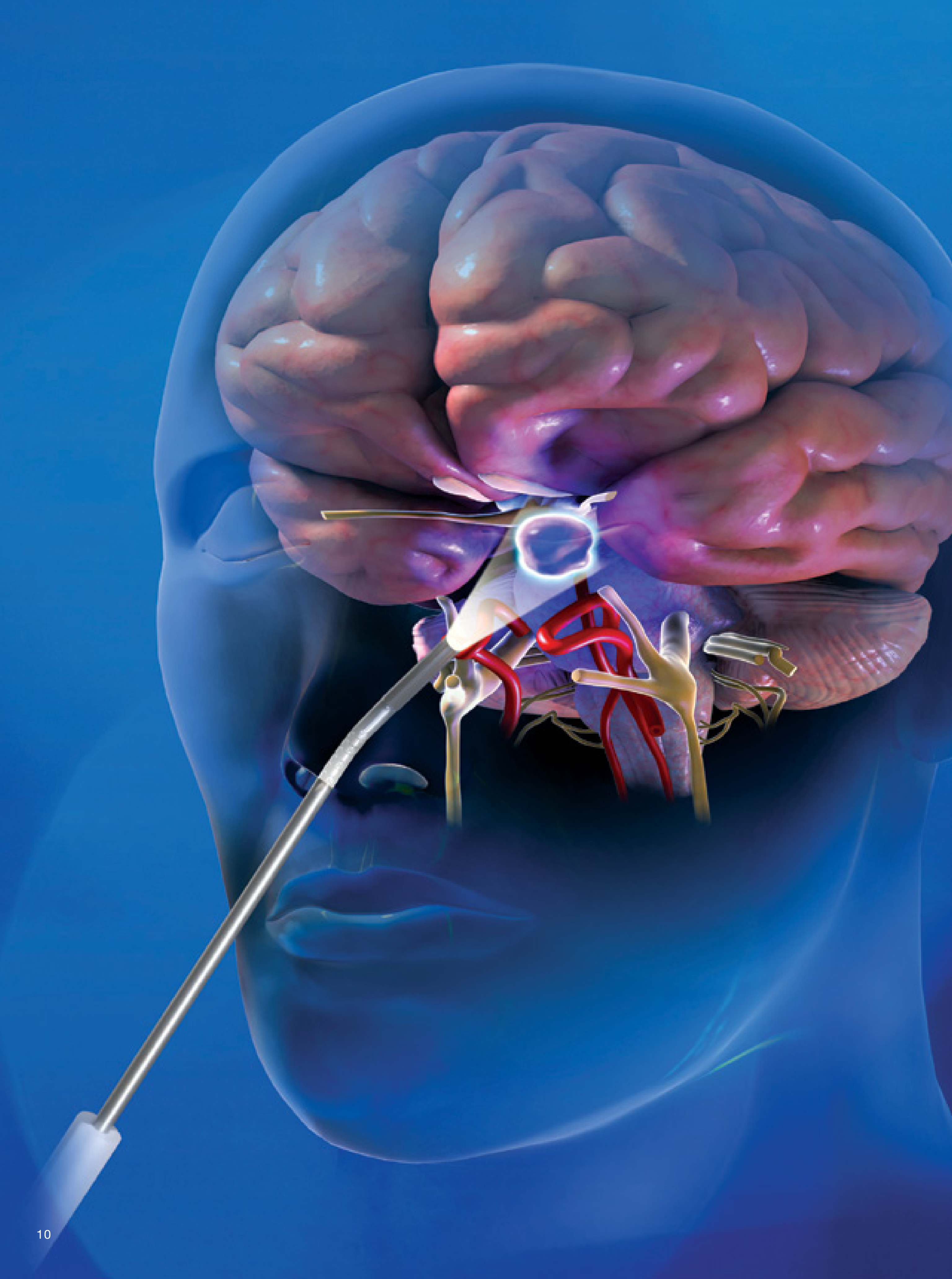
NASA's Neutron-star Interior Composition Explorer (NICER) X-ray instrument — to be deployed on the International Space Station in 2017 — will gather data about neutron stars, the remnants of massive stars that, after exhausting their nuclear fuel, exploded and collapsed into spheres about the size of New York City. Their intense gravity crushes an astonishing amount of matter — at least 460,000 Earths — creating the densest objects known in the universe. Observing in the X-ray band offers the greatest insights into their structure and the dynamic phenomena that they host, including star-quakes, thermonuclear explosions, and the most powerful magnetic fields known in the universe. Through JPL's Strategic University Research Program, MDL is collaborating with the Massachusetts Institute of Technology (MIT) to develop devices for potential use on the mission.

Image courtesy FLIR Systems Inc.

WORKING TOGETHER FOR ENHANCED SURVEILLANCE AND SECURITY

MDL is working to develop the most advanced infrared imaging devices through partnerships with multiple industry partners.

MDL is a leader in infrared imaging technology and actively partners with private industry partners to create innovative devices for use by NASA, the Department of Defense, law enforcement, and other national agencies for activities such as airborne and ground-based surveillance, navigation, border and maritime patrol, and search and rescue. These technologies make it possible to see one's environment with or without visible illumination, as illustrated by this nighttime photograph in Paris, France. Cameras aided by these technologies can also see through smoke, fog, haze, and other atmospheric obscurants to detect potential dangers that cannot be seen with the naked eye. As MDL continues to work with industry partners to advance these technologies, we are finding growing commercial applications that include flight and automotive navigation, building inspection, home security, and medical imaging, to name a few.



WORKING TOGETHER TO IMPROVE HOW WE OPERATE ON THE BRAIN

Skull Base Institute is partnering with MDL to develop the next generation of endoscopic tools.

MARVEL (Multi-Angle Rear-Viewing Endoscopic Tool) is a revolutionary instrument bringing together sweeping advancements in digital imaging, 3D endoscopy, and smart microtechnology. MARVEL includes a tiny high-definition stereo camera and an illumination system mounted on the tip of a miniature tool, constituting an endoscope. Although the technology previously existed for 2D imaging endoscopes at this size for minimally invasive neurosurgeries, MARVEL brings together for the first time a stereo imaging camera and its side-to-side sweeping capability for this application. The benefits are significant. While smaller endoscopes and thinner instruments allow for smaller incisions and lesser disruption to surrounding tissues and structures, seeing the tumor in 3D and in high definition allows the surgeon superior visibility, depth perception, and the ability to place surgical tools with the utmost precision.

Herschel artwork courtesy ESA. Artist's illustration of Ceres by NASA/JPL-Caltech.

WORKING TOGETHER TO UNDERSTAND OUR EVOLVING UNIVERSE

MDL devices for the Planck and Herschel missions have made significant contributions to our knowledge of the universe.

Launched in 2009, the Planck and Herschel missions have provided numerous discoveries to the science community. These European Space Agency (ESA) missions have significant NASA participation, with three out of their five science instruments enabled by MDL technologies. For example, MDL's spiderweb bolometers enabled Planck and the Herschel SPIRE instrument to deliver state-of-the-art maps of the universe at millimeter and far-infrared wavelengths. Most recently, scientists using Herschel's Heterodyne Instrument for the Far-Infrared (HIFI), which also relies on MDL devices, have made the first definitive detection of water vapor on the dwarf planet Ceres in the asteroid belt. The results come at the right time for NASA's Dawn mission. Currently on its way to Ceres and scheduled to arrive in 2015, Dawn will take the closest look ever at its surface.

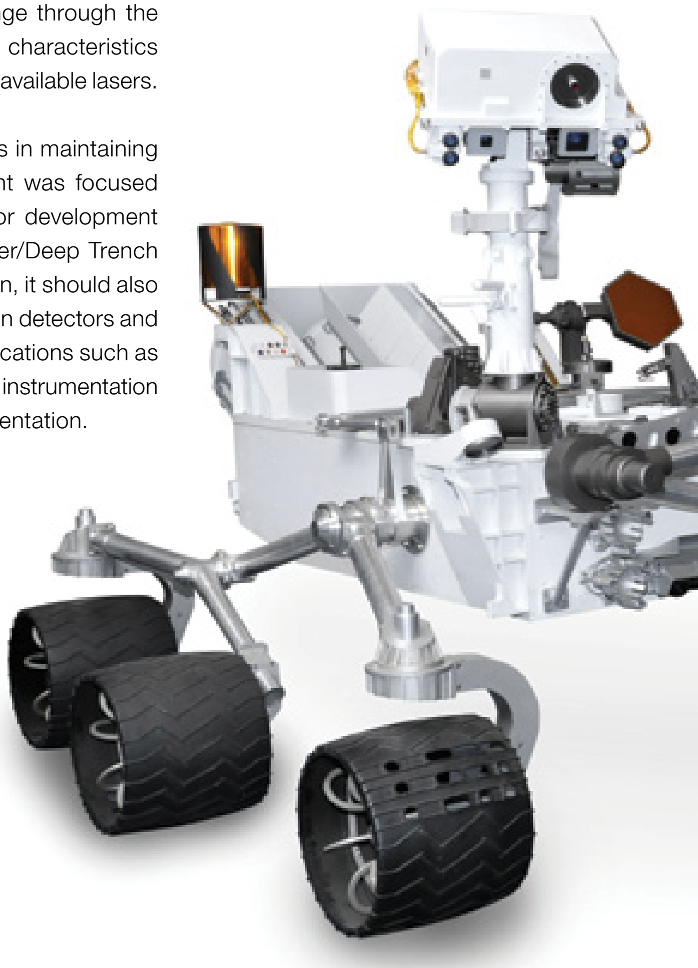
Letter from the Microdevices Laboratory

Important collaborations between MDL and external partners from universities, industry, and various branches of government have resulted in an explosion of achievements this past year: 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 micro technologies for industry, medical health, 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.

To fuel this vibrant environment, we have continued our investments in maintaining the Microdevices Laboratory as a state-of-the-art facility.

Our collaborations with universities are particularly exciting. MDL technology — superconducting detector arrays — fundamentally enabled the recently announced discovery of B-mode polarization of the cosmic microwave background. This measurement provides critical evidence for gravitational waves rippling through the infant universe, generated by the massive inflation that occurred when the universe was only 10^{-35} seconds old. This breakthrough result was the fruit of a long-standing partnership between JPL and the Caltech campus that included collaborations with a number of other universities. Second, our collaboration with Harvard University is enabling new insight into Earth stratospheric–tropospheric exchange through the delivery of semiconductor lasers with unprecedented performance characteristics that represent an order of magnitude improvement over commercially available lasers.

To fuel this vibrant environment, we have continued our investments in maintaining the MDL as a state-of-the-art facility. This year's major investment was focused on greater capability in submillimeter- and millimeter-wave detector development for astrophysics applications. Although the new Deep Silicon Etcher/Deep Trench Reactive Ion Etcher will prove useful in the aforementioned application, it should also prove useful for our existing micromachined gyroscopic angular motion detectors and microthruster technologies that can be applied to small satellite applications such as CubeSats. The investments are synergistic with JPL's new initiatives in instrumentation for CubeSat-based science missions and CubeSat systems implementation.



Pictured from left to right:
Dr. Tom Luchik (Instrument Division Manager),
Dr. Chris Webster (MDL Director),
Dr. Jonas Zmuidzinas (JPL Chief Technologist),
Dr. Siamak Forouhar (MDL Deputy Director), and
James Lamb (MDL Manager).

MDL's success is created by its outstanding research staff, and this year we mourn the loss of our brilliant colleague and friend Dr. Jeffrey Stern, whose remarkable achievements are highlighted on page 76.

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, we 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 remains in creative innovations in miniaturized technologies that contribute to the national interest.

Sincerely,

Dr. Christopher Webster	Dr. Thomas S. Luchik
Director	Manager
JPL Microdevices	Instruments and Science
Laboratory	Data Systems Division

While the pace of discovering new planets is accelerating, most are discovered indirectly, without an image of the planet. Researchers at JPL have teamed up with Ruslan Belikov of NASA's Ames Research Center and Olivier Guyon of the University of Arizona and Subaru Telescope to directly image exoplanets, because the search for life cannot take place without this technique. Light reflected from the planet is a necessary component for spectroscopic observations, which are used to determine the chemical composition of planets and the possibility of life. Learn more about MDL's contributions on page 19.

© Image courtesy Andrew Richard Hara Photography.

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.

MDL develops electron-beam lithography techniques to fabricate unique nanostructures and optics that enable JPL instruments to perform novel measurements. The development of reliable binary nanopatterning processes as well as unique analog (grayscale) lithography processes to fabricate surface relief profiles in polymers and substrate materials has allowed the creation of nearly arbitrary transmissive and reflective diffractive optics such as blazed gratings, lenses, and computer-generated holograms, for wavelengths ranging from ultraviolet to long-wave infrared. Further, we have developed custom e-beam calibration techniques, substrate mounting fixtures, and pattern preparation software to allow fabrication of these diffractive optics on nonflat (convex or concave) substrates with several millimeters of height variation. This has enabled the fabrication of high-performance convex and concave diffraction gratings for Offner and Dyson type imaging spectrometers that have been used for many airborne and spaceborne instruments. >>

Above: Immersion grating on glass prism produced at JPL's Microdevices Laboratory.

Large Gratings under Development for Next-Generation Imaging Spectrometers for Global Daily Tracking of Atmospheric Gases

The next generation of imaging spectrometers will aim to measure wide swaths of the ground or atmosphere in a single satellite orbit or aircraft flight. This increased swath width requires wide-angle optical systems, which in turn require larger gratings with increased center-to-edge height sag. Both Offner and Dyson imaging spectrometer designs are envisioned, which require convex and concave gratings, respectively. MDL is currently extending e-beam fabrication techniques to allow these larger gratings to be fabricated with high precision in reasonable exposure times.

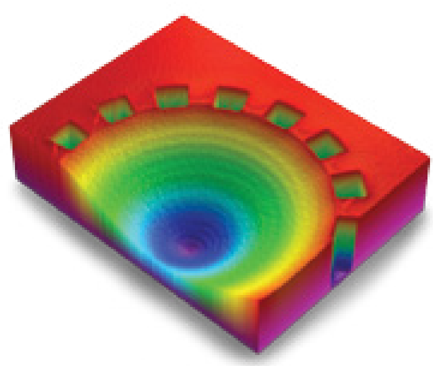
Fabrication techniques are also in development for immersion gratings on which the light is incident from within the substrate material, typically a prism made of high-refractive index glass or infrared transmissive silicon. Because the light wavelength inside the substrate is reduced by the refractive index, the required grating and optical system size to achieve a given resolving power or dispersion is also reduced. Optical designs that utilize immersion gratings to realize smaller, lighter, high-resolution wide-swath imaging spectrometers are being considered for future missions that aim to measure the global distribution of atmospheric gases on a daily basis. To fabricate immersion gratings, JPL is pursuing multiple approaches, including MDL's analog e-beam lithography process as well as binary e-beam lithography, followed by wet anisotropic silicon etching at the University of Texas at Austin through a collaboration with a group led by Professor Dan Jaffe.

Deep Grayscale E-Beam Lithography and Silicon Etching in Support of Planet-Finding Studies and Electrospray-Propelled Vehicles

Scientists at MDL have developed a deep grayscale electron-beam lithography and plasma etching process for fabricating three-dimensional surface relief profiles in thick polymer resists and silicon substrates. The plasma etching process amplifies the depth of the grayscale e-beam resist pattern and thus can be used to realize shaped silicon structures that are tens of microns deep.

This unique fabrication technique was successfully used to deliver achromatic infrared coronagraph occulting masks designed by Kevin Newman, Olivier Guyon (University of Arizona), and Ruslan Belikov (NASA's Ames Research Center) for testing at the Ames Coronagraph Experiment (ACE) laboratory as well as the Subaru Telescope, as part of an effort to develop new technologies for planet-finding studies. The initial tests were successful and improved masks are being designed and fabricated.

The grayscale etching technique is also being used as part of a process to fabricate shaped silicon needles for electrospray propulsion thrusters under development at MDL (see page 59).



Above: Infrared transmissive silicon phase masks were fabricated at MDL and delivered for testing at the Ames Coronagraph Experiment (ACE) laboratory and at the Subaru Telescope (pictured below). Results showed that the mask performed as intended and future iterations are in development.

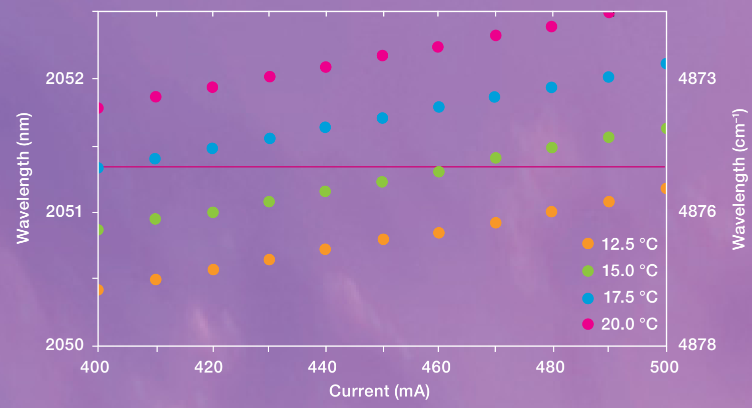
A storm approaches Brighton Beach, New York. The frequency and intensity of summer storms such as this are expected to increase with climate change. Ozone destruction by human-made chlorofluorocarbons (CFCs) typically occurs only at very cold temperatures, but scientists have discovered that the unusual presence of water vapor raises the temperature at which ozone loss can take place. A partnership between Harvard University and MDL leverages the strengths of both to yield innovative technologies for the active detection of chemically important trace species in Earth's atmosphere for the continued study of its effects on our environment. Read more on page 25.

SEMICONDUCTOR LASERS

Tunable laser spectrometer instruments using the MDL semiconductor lasers are capable of measuring emission rates of carbon dioxide and methane on Earth and other planets.

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. Stable isotope ratios of H, C, and O are powerful indicators of a wide variety of planetary geophysical processes, and for Mars they reveal the record of loss of its atmosphere and subsequent interactions with its surface such as carbonate formation. The in situ measurements of the isotopic ratios of D/H and $^{18}O/^{16}O$ in water and $^{13}C/^{12}C$, $^{18}O/^{16}O$, $^{17}O/^{16}O$, and $^{13}C^{18}O/^{12}C^{16}O$ in carbon dioxide in the martian atmosphere were made from the Curiosity rover using the Sample Analysis at Mars (SAM) tunable laser spectrometer (TLS). >>

Evening view of factories in Shanghai, China. Over the past century, human activities have released large amounts of carbon dioxide and other greenhouse gases into the atmosphere. To better understand the global carbon cycle's effect on climate change, MDL is developing high-power lasers that will enable uninterrupted, all-season measurements at high latitudes and at night — a capability presently unavailable in current monitoring models.

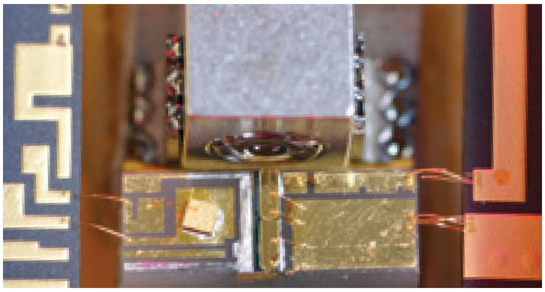


Above: A semiconductor laser's wavelength tunes across a CO_2 absorption line with both its current and temperature. The solid line marks the spectral position of a CO_2 absorption line at 4875.749 cm^{-1}.

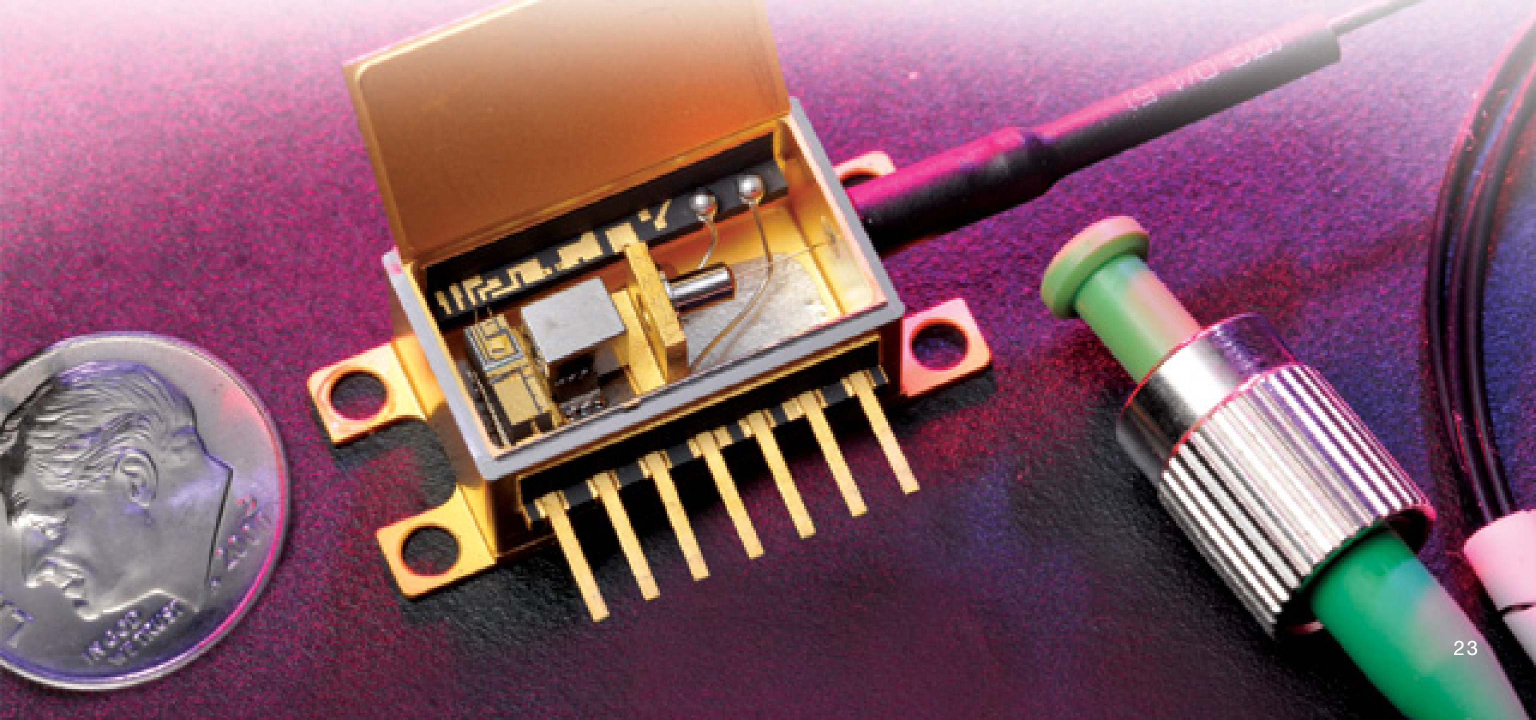
World's First High-Power 2.05 µm Fiber-Coupled Seed Semiconductor Laser Will Help Measure Greenhouse Gases from Space

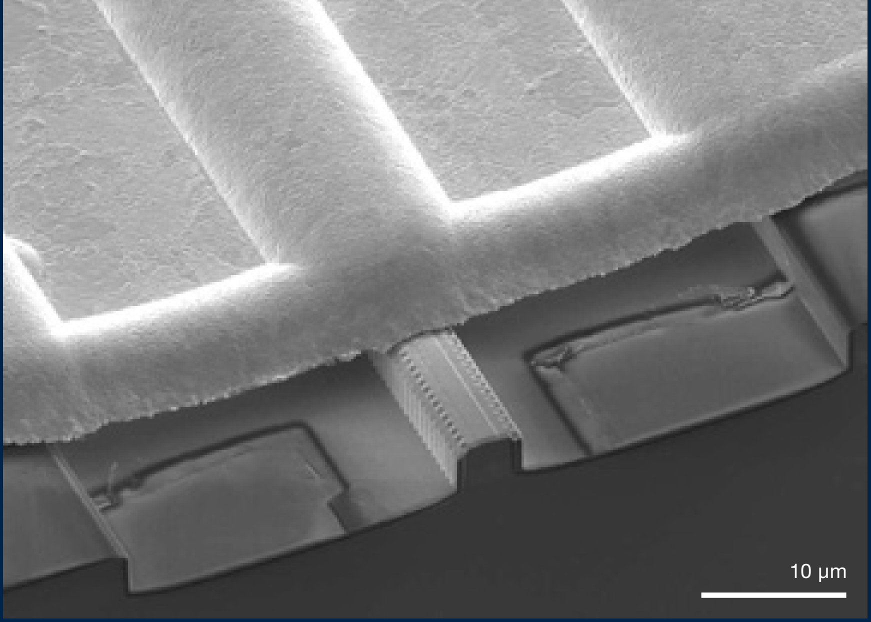
Observing the global carbon cycle plays an important role in our understating of climate change. Active (lidar) remote sensing of atmospheric CO_2 concentration would enable uninterrupted, all-season measurements at high latitudes and at night that are presently unavailable with the current passive measurement schemes. In support, MDL has demonstrated fiber-coupled distributed-feedback (DFB) semiconductor lasers with record high output power (more than 20 mW) operating near the 2.051 µm wavelength — an important milestone in advancing airborne lidar systems for CO_2 detection. These modules will enable, for the first time, the use of semiconductor diode lasers in injection seeding applications of high-power lidar transmitters for 3D wind measurement and CO_2 detection at the preferred wavelength of 2.0 µm and 2.05 µm, respectively.

With the recent progress in the development of optical fiber amplifiers operating near 2.05 µm wavelength, MDL's high-power fiber-coupled semiconductor laser will be an enabling technology for a myriad of other emerging applications in this wavelength range.



Above: A laser chip mounted on an aluminum nitride (AlN) submount and soldered to a temperature-controlled heatsink. The laser output power is collected and focused via a single-element optical lens. Bottom: In the hermetically sealed package, optical elements with anti-reflection coating layers with a single-stage optical isolator are used to suppress back-reflection into the laser cavity.

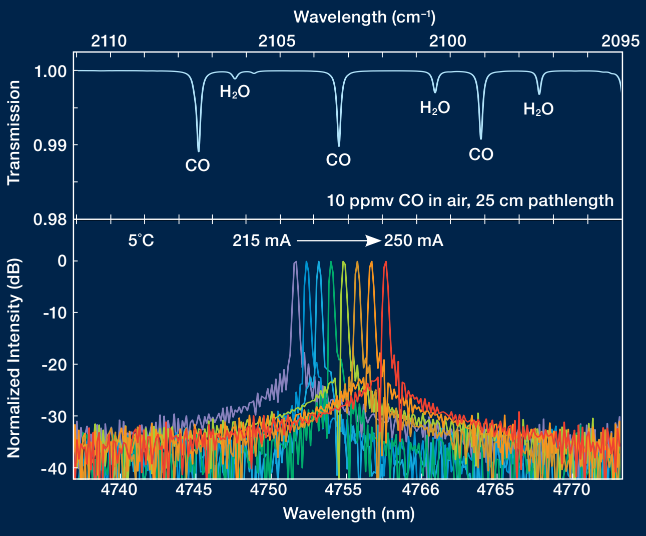




Above: This scanning electron micrograph shows the emission facet of a single-frequency quantum cascade laser. Below: MDL's electrically driven quantum cascade lasers are designed to precisely tune across strong absorption lines of carbon monoxide at mid-infrared wavelengths, as shown by laser emission spectra collected as a function of injection current.

Laser Absorption Spectroscopy for Combustion Product Monitoring

NASA needs more than an ordinary household smoke detector to ensure the safety of astronauts living more than 200 miles above the surface of Earth. Using specialized semiconductor lasers to probe molecular absorption lines at infrared wavelengths, instruments developed at MDL can provide a real-time record of hazardous gas concentrations with remarkable sensitivity and specificity. These instruments will enable rapid response to accidental fires aboard manned spacecraft by sniffing out the slightest increase in the levels of poisonous gases generated by burning batteries, wiring, and electronics packaging. The latest instrument using lasers fabricated at MDL can simultaneously monitor CO, HCl, HCN, HF, and CO_2 levels in the air to not only indicate the presence of combustion, but also help identify the material being burned.



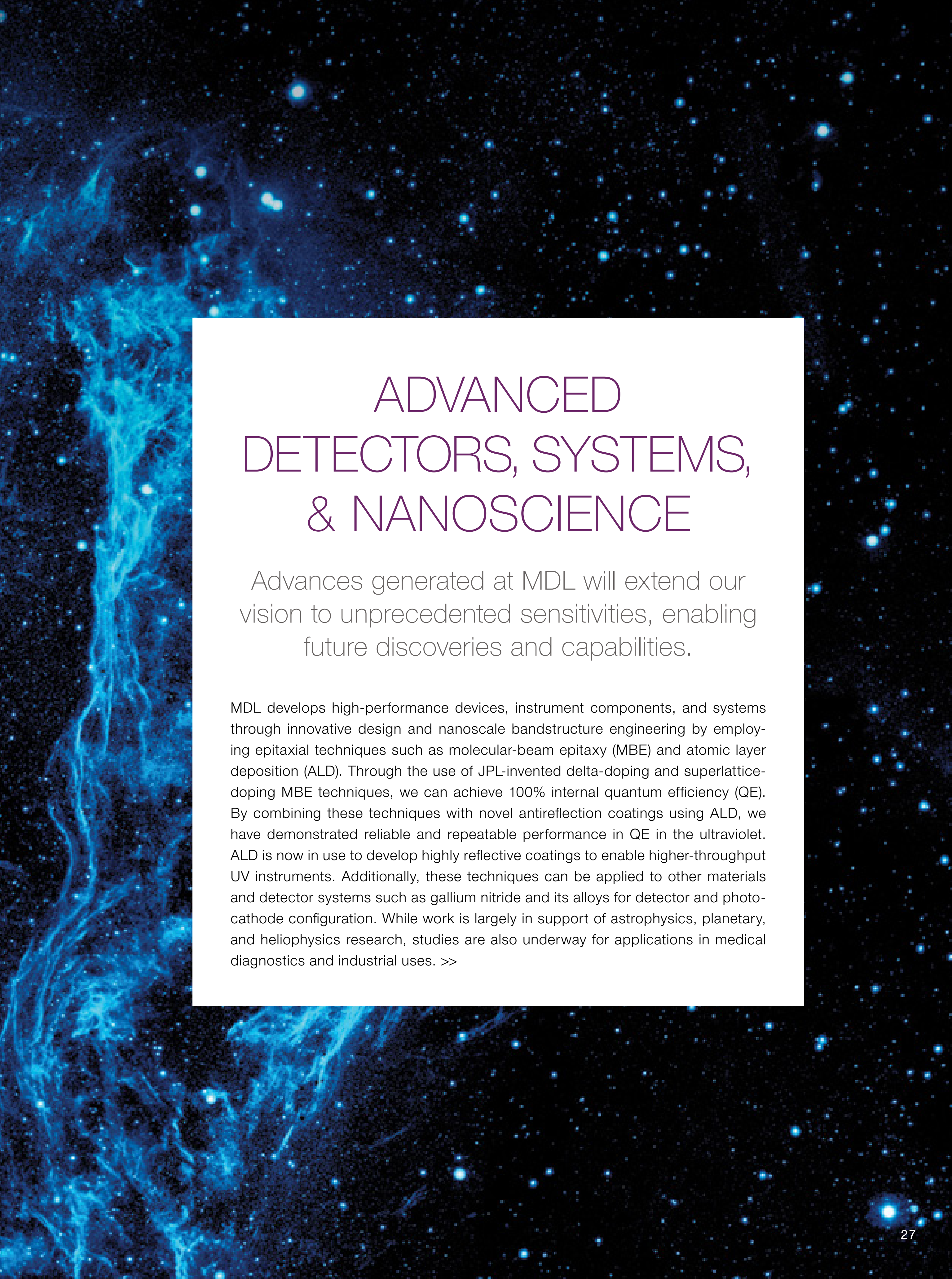
MDL Device Helps Determine the Relationship Between Water Vapor and Mid-Latitude Ozone Loss

In order to thoroughly characterize atmospheric composition at all altitudes, an unprecedented scientific and technical effort is needed. Essential to the advancement of both remote-sensing and in situ science are improvements in continuous-wave (CW) and high-energy pulsed laser systems in the mid-infrared (mid-IR) spectral region to bridge the long-standing gap in commercially available technology. Sources in the spectral region from 2.8 μm to 3.5 μm are crucial to the sensitive and precise quantification of several chemically and climatically relevant atmospheric trace species, including OH, H_2O, $H_2{}^{18}O$, HDO, CH_4, $^{13}CH_4$, CO_2, CH_2O, and C_2H_6, all of which present strong fundamental vibrational absorptions in this range.

Partnering MDL's technical expertise in laser development with the scientific and engineering capabilities of Anderson Research Group at Harvard University to deploy cutting-edge in situ instruments for the measurement of these gases has proved extremely successful. The collaboration has promoted the development of single-frequency mid-IR diode lasers primarily intended for use as CW optical sources for in situ absorption spectroscopy utilizing long-pathlength multipass cells. JPL has developed and delivered single-frequency tunable CW lasers at ~2.65 μm with unprecedented performance characteristics. The delivered lasers produced more than 30 mW of output power, which represents an order of magnitude improvement over commercially available lasers at similar wavelengths. The subsequent integration of these lasers with Harvard's high-performance, miniaturized electronics control suite and specially designed and field-tested optical system and instrumentation provides a package for the detection of water and its deuterated isotopologue, HDO, with greatly enhanced sensitivity and accuracy. These measurements are critical to the study of water vapor transport into the stratosphere and its effect on the chemistry of key halogens such as HCl as they relate to ozone loss.

Below: A rain cloud over the sea near the Philippines. Should the growing intensity of summer storms lead to a vapor-rich stratosphere, the likely depletion of stratospheric ozone would allow more DNA-damaging ultraviolet radiation to reach Earth, with potential biological effects on human beings, animals, and plants.

Tendrils of hot dust and gas glow brightly in this ultraviolet image of the Cygnus Loop nebula, taken by NASA's recently retired Galaxy Evolution Explorer (GALEX). The nebula is a supernova remnant from a massive stellar explosion that occurred between 5,000 to 8,000 years ago. Filaments of gas and dust visible here in ultraviolet light were heated by the shockwave from the supernova, which is still spreading outward. The original explosion would have been bright enough to be seen clearly from Earth with the naked eye. MDL is developing next-generation detectors that have significantly higher sensitivities than on GALEX and the potential to reveal new discoveries on future missions. Read more on page 30.



ADVANCED DETECTORS, SYSTEMS, & NANOSCIENCE

Advances generated at MDL will extend our vision to unprecedented sensitivities, enabling future discoveries and capabilities.

MDL develops high-performance devices, instrument components, and systems through innovative design and nanoscale bandstructure engineering by employing epitaxial techniques such as molecular-beam epitaxy (MBE) and atomic layer deposition (ALD). Through the use of JPL-invented delta-doping and superlattice-doping MBE techniques, we can achieve 100% internal quantum efficiency (QE). By combining these techniques with novel antireflection coatings using ALD, we have demonstrated reliable and repeatable performance in QE in the ultraviolet. ALD is now in use to develop highly reflective coatings to enable higher-throughput UV instruments. Additionally, these techniques can be applied to other materials and detector systems such as gallium nitride and its alloys for detector and photocathode configuration. While work is largely in support of astrophysics, planetary, and heliophysics research, studies are also underway for applications in medical diagnostics and industrial uses. >>

Above: A close-up of one of the devices delivered to RAL. Multiple CMOS arrays were processed for low energy X-ray detection on 8-inch wafers using superlattice doping.

Custom Wafer-Scale CMOS Array for Low-Energy X-Ray Detector Development in Partnership with Rutherford Appleton Laboratory

A partnership has commenced between Rutherford Appleton Laboratory (RAL) in Oxford, England, and the MDL to develop wafer-scale complementary metal-oxide-semiconductor (CMOS) arrays for low-energy X-ray detection. Although the intended use of this detector development is for a synchrotron, this low energy X-ray detector can be used for instruments in future missions.

In the first phase of work, MDL worked with smaller-scale arrays to establish proof of concept. This first set of detectors has been delivered to RAL for testing and feedback. The wafer-scale design is completed and will be processed in the second phase of the project, expected in 2014.

Broadband Detectors for On-Sky Observation

On-sky observations with broadband delta-doped arrays were planned as part of an effort funded by NASA's Strategic Astrophysics Technology (SAT). Delta-doped p-channel devices were previously developed in collaboration with Lawrence Berkeley National Laboratory (LBNL). These detectors were processed using MDL's large-capacity silicon MBE, and the broadband coating used was developed using ALD to maximize the response over the required range (320–1000 nm). This is the baseline detector for an Explorer-Orion mission concept, and on-sky observation is a necessary step for laboratory devices to showcase their capabilities and demonstrate their viability for future missions. Thus, three prototype LBNL detectors were delivered to Arizona State University for testing at Arizona's Kitt Peak National Observatory.

MDL is also working with Semiconductor Technologies Associates (STA) and Teledyne DALSA to develop delta-doped n-channel detectors with similar broadband performance for the 200-inch Hale Telescope at Caltech's Palomar Observatory. These 4-megapixel arrays will be primarily used for the guide and focus functions in WaSP (Wafer Scale Prime), a replacement instrument for the Hale Telescope's current Large Format Camera. Due to their extended response in the blue and red ends of the spectrum, the arrays allow additional capabilities that can be used by observers.

Below: A JPL delta-doped large-format CCD is inspected prior to delivery for on-sky observations at Kitt Peak National Observatory in Tucson, Arizona.

Above: This side-by-side comparison shows the nearby galaxy Messier 81. While the visible-light image from the National Optical Astronomy Observatory reveals the distribution of stars (left), an ultraviolet-light image shows the most active, young stars (right). The ultraviolet image, taken by the Galaxy Evolution Explorer (GALEX), reveals that the galaxy’s spiral arms are dotted with pockets of violent star-forming activity.

Large-Format, High-Efficiency Detector Will Help Discover and Map Faint Emission from the Intergalactic Medium

FIREBALL-2 (Faint Intergalactic Redshifted Experiment Balloon) is a follow-up Caltech mission to discover and map faint emission from the intergalactic medium. While FIREBALL-1 used a GALEX spare detector based on a microchannel plate, this next-generation detector, also developed by MDL, is a 2-megapixel delta-doped, custom antireflection (AR)–coated electron multiplied CCD (EMCCD) array. This combination creates a detector capable of photon counting with a much higher QE. Our previous single-layer AR coatings designed for a GALEX follow-on mission concept demonstrated nearly an order of magnitude improvement over the GALEX detector by showing a 50% QE in a 0.5 megapixel format. The new design shows nearly 80% QE in the narrowband window in the atmosphere at 205 nm. In addition, the pixel count was increased by a factor of four, making the technology of interest for future astrophysics and planetary missions.

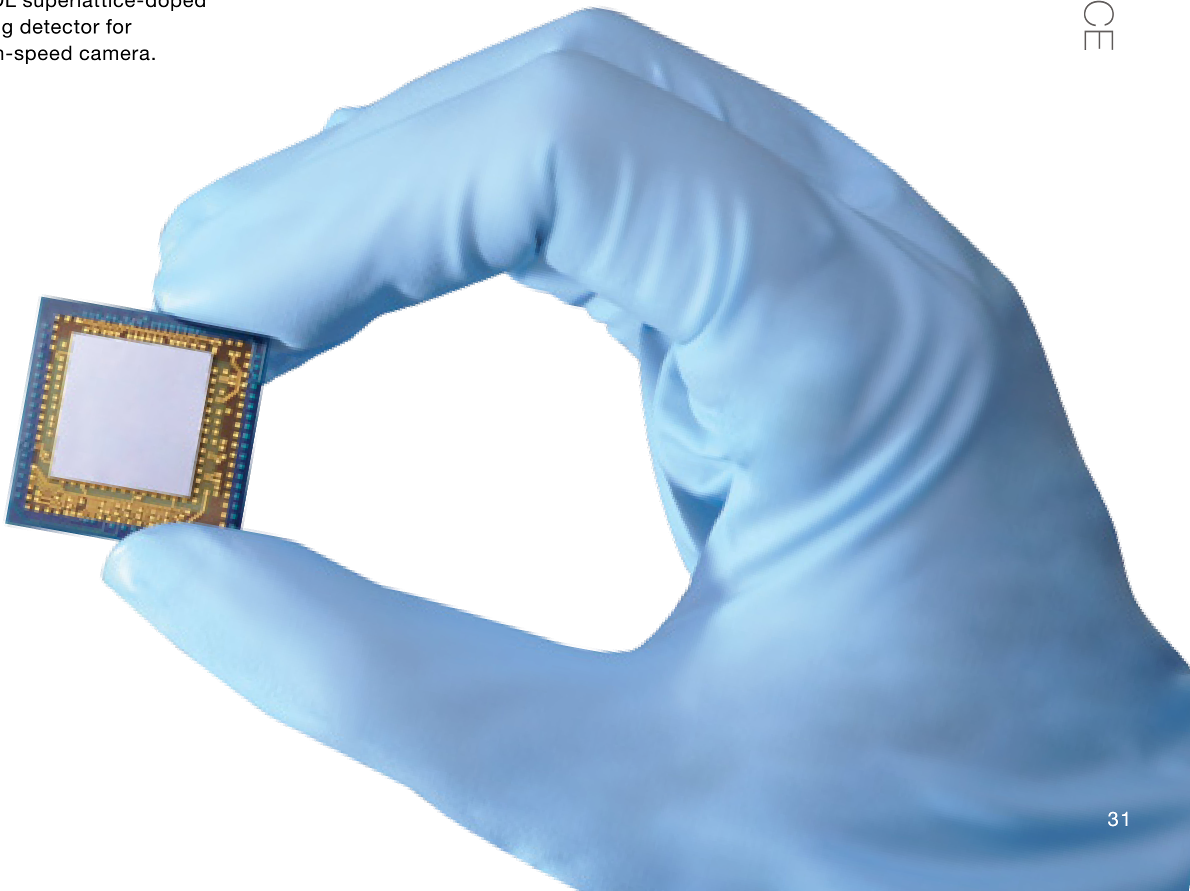
MDL Superlattice-Doped Detectors Provide Unprecedented Stability and Performance

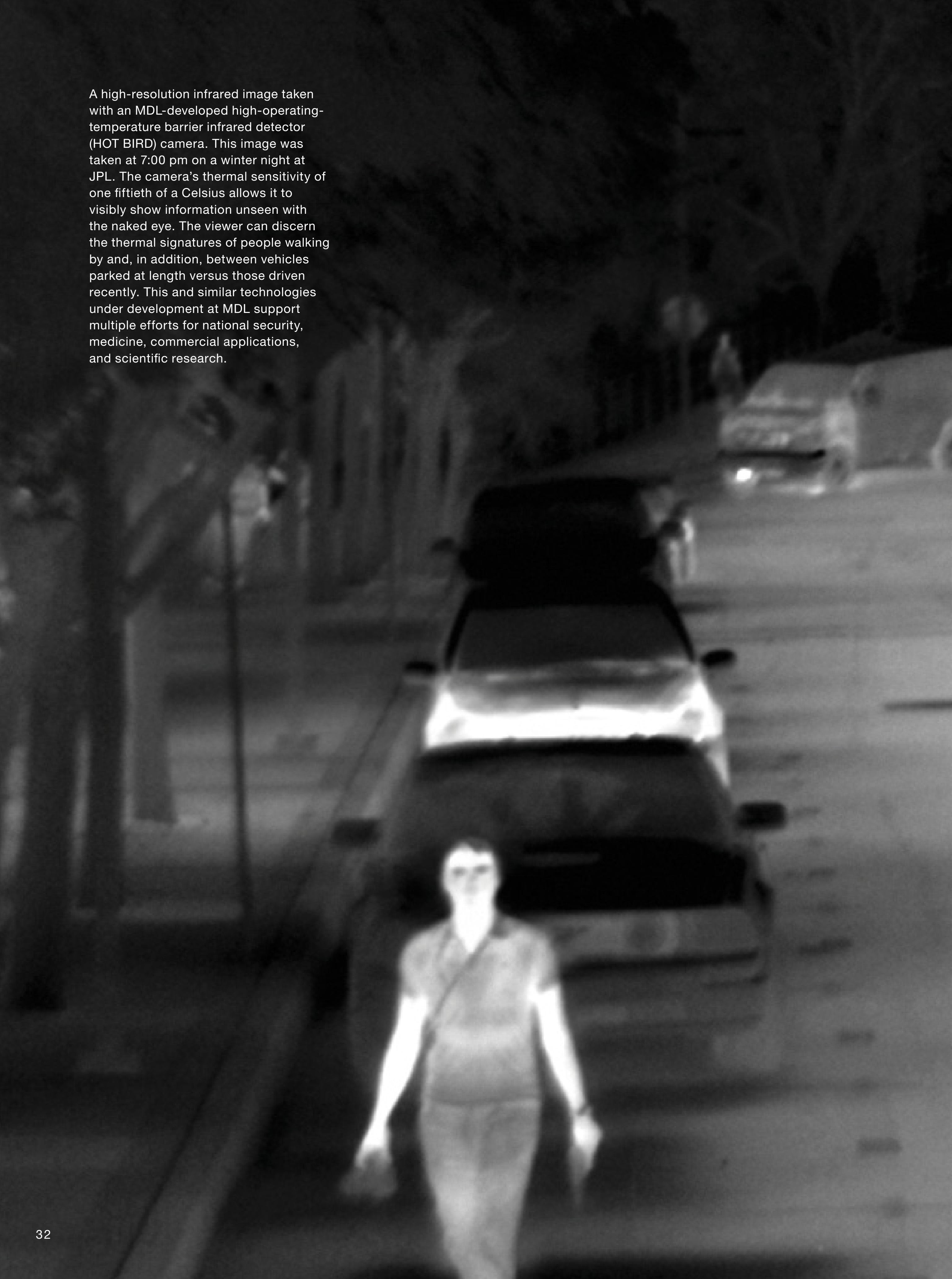
Despite over 40 years of development, backside-illuminated detectors are not sufficiently stable for many applications. MDL has developed superlattice-doped detectors with exceptional stability and quantum efficiency (QE) in the deep and far-UV. Superlattice doping represents a fundamentally different approach to surface passivation than conventional methods of ion implantation and diffusion. The structure of the superlattice comprises multiple layers of delta-doped silicon grown by molecular-beam epitaxy. Its stability enables nearly 100% charge collection efficiency independent of the density of interface traps.

MDL recently partnered with Alacron, Inc. to develop a high-speed imaging camera in which superlattice-doped CMOS imaging detectors provide the essential stability and sensitivity for deep ultraviolet (DUV) lithography applications in the semiconductor industry. The detectors achieve nearly 100% internal QE in the deep and far-UV with a 64% external QE at 263 nm. In lifetime tests performed at Applied Materials, the QE and dark current of the camera remained stable to better than 1% precision during long-term exposure to several billion laser pulses, with no measurable degradation, no blooming, and no image memory at 1000 fps.

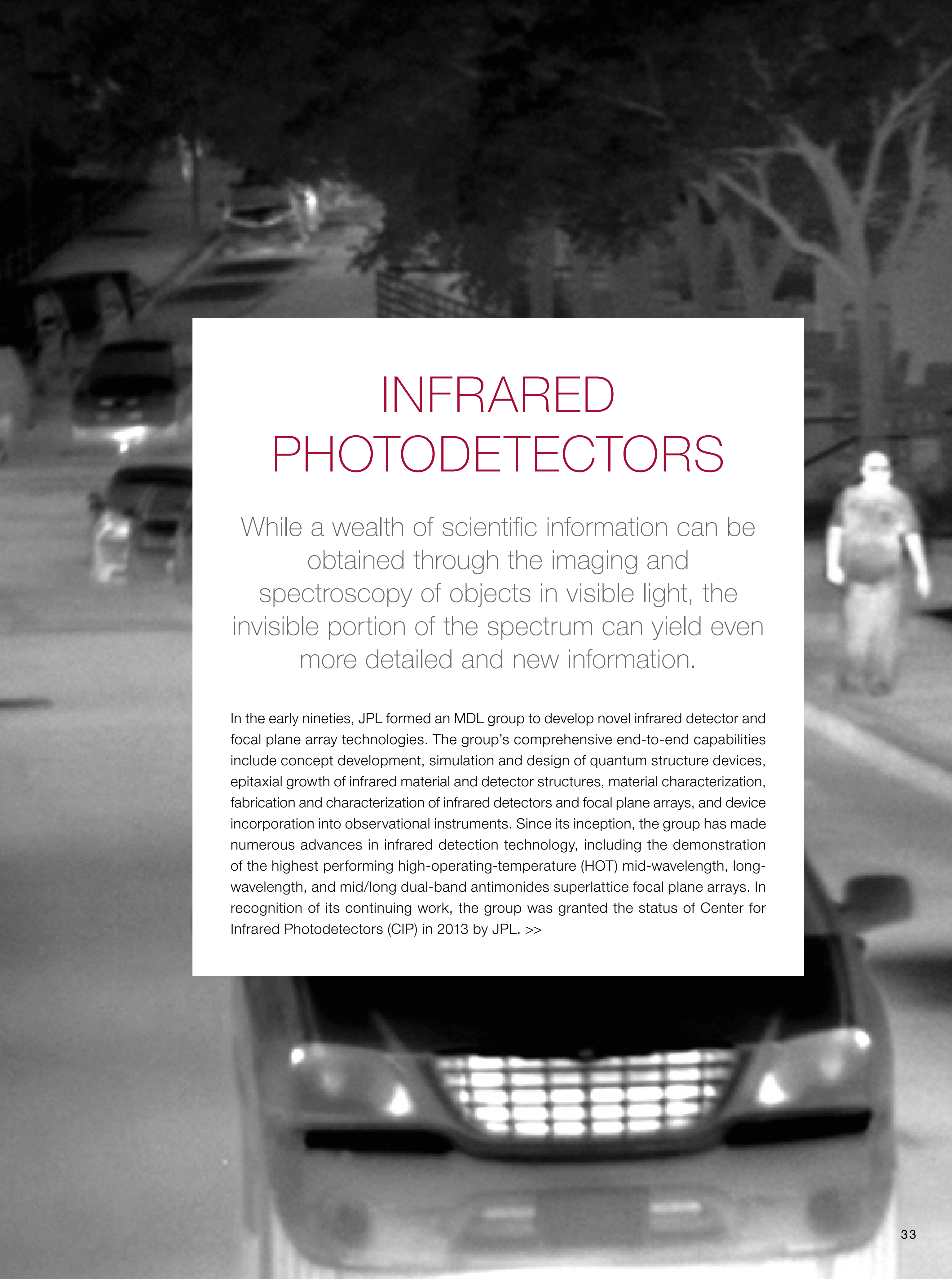
MDL is now working with industry and university partners on further development and applications of superlattice-doping technology for DUV lithography, electron microscopy, and high-sensitivity photon and particle detection.

Below: An MDL superlattice-doped CMOS imaging detector for Alacron's high-speed camera.





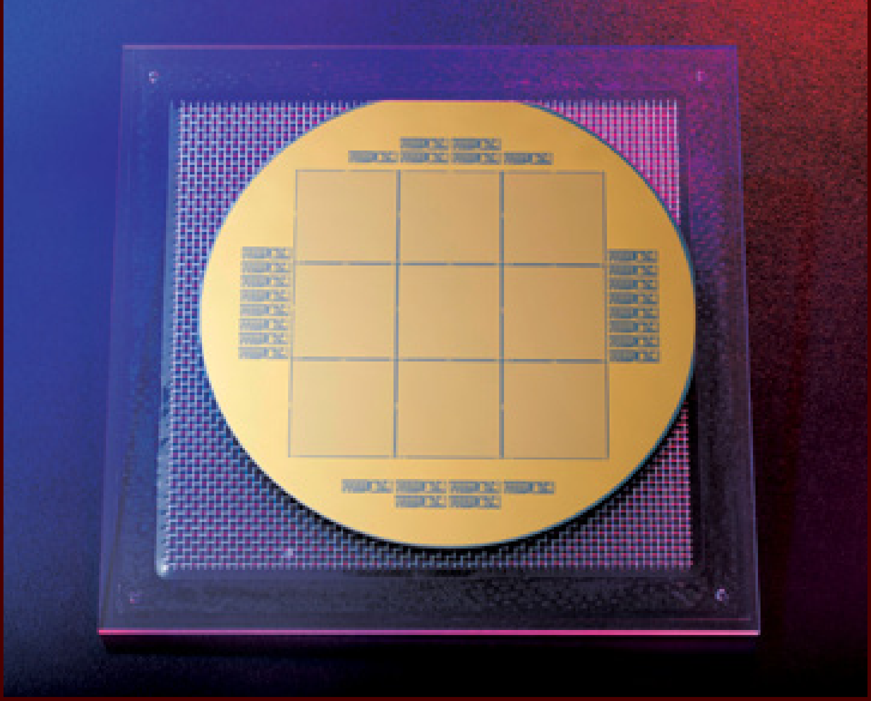
A high-resolution infrared image taken with an MDL-developed high-operating-temperature barrier infrared detector (HOT BIRD) camera. This image was taken at 7:00 pm on a winter night at JPL. The camera's thermal sensitivity of one fiftieth of a Celsius allows it to visibly show information unseen with the naked eye. The viewer can discern the thermal signatures of people walking by and, in addition, between vehicles parked at length versus those driven recently. This and similar technologies under development at MDL support multiple efforts for national security, medicine, commercial applications, and scientific research.



INFRARED PHOTODETECTORS

While a wealth of scientific information can be obtained through the imaging and spectroscopy of objects in visible light, the invisible portion of the spectrum can yield even more detailed and new information.

In the early nineties, JPL formed an MDL group to develop novel infrared detector and focal plane array technologies. The group's comprehensive end-to-end capabilities include concept development, simulation and design of quantum structure devices, epitaxial growth of infrared material and detector structures, material characterization, fabrication and characterization of infrared detectors and focal plane arrays, and device incorporation into observational instruments. Since its inception, the group has made numerous advances in infrared detection technology, including the demonstration of the highest performing high-operating-temperature (HOT) mid-wavelength, long-wavelength, and mid/long dual-band antimonides superlattice focal plane arrays. In recognition of its continuing work, the group was granted the status of Center for Infrared Photodetectors (CIP) in 2013 by JPL. >>



Above: 20-micron pixel-pitch 9-megapixel detector arrays fabricated on a 4-inch GaSb wafer. This same layout scheme can be used to fabricate 10-micron pixel-pitch nine 4-megapixel detector arrays on a 4-inch GaSb wafer.

Development of Technologies Based on III-V Compound Semiconductor Heterostructures Continues

An important goal of the CIP is to develop infrared technologies based on III-V compound semiconductor heterostructures. In 2013, work continued on four types of infrared detectors based on III-V compound semiconductors such as III–arsenides, III–phosphides, and III–antimonides. III-V compound semiconductors are based on strong covalent bonds and are much harder than their infrared counterpart — II-VI compound semiconductors — which are more ionic and softer. As a result, III-V compound semiconductors are available in large-diameter wafers such as 8-inch GaAs and 4-inch GaSb, which are easier to grow and to process into large-area arrays. Mid-wave infrared (MWIR) focal plane arrays (FPAs) find many applications in space, defense and security, and industry. The current MWIR FPA market is dominated by those based on InSb, complemented in much smaller quantities by HgCdTe mercury–cadmium–telluride (MCT)–based FPAs for very high-performance applications. While InSb offers lower cost, better manufacturability, and large-format capability, it operates at substantially lower temperature (80 K) than MCT with a comparable cutoff wavelength. A recent breakthrough in MWIR detector design (patents pending), has resulted in a high-operating-temperature (HOT) barrier infrared detector (BIRD) that is capable of spectral coverage of not only the entire MWIR atmospheric transmission window (3–5 μm), but also the short-wave infrared (SWIR; 1.4–3 μm), the near-infrared (NIR; 0.75–1.4 μm) and the visible bands, which could enable many space remote-sensing applications. Furthermore, the cutoff wavelength of the HOT BIRD is adjustable, while that for InSb is fixed at ~5.3 μm. Compared to the MWIR MCT, the HOT BIRD enjoys manufacturability, cost, material robustness, and large-format array capability advantages.

Infrared Imaging in Support of NASA Missions and National Security

MDL's CIP is engaged in the development of quantum-well infrared photodetectors (QWIPs), quantum-dot infrared photodetectors (QDIPs), superlattice barrier infrared detectors (BIRDs) and large-area infrared focal plane arrays based on these detector technologies.

The development of large-area focal plane arrays for infrared imaging is made possible through investment by NASA, the Department of Defense, and other government agencies and private industries. Because cameras aided by these technologies can see through smoke, fog, haze, and other atmospheric obscurants better than a visible-light camera can, these devices are optimal for flight navigation, security surveillance, and reconnaissance. Thermal infrared instruments are also vital to NASA space and Earth science studies including missions studying global ecosystems, which will provide critical information on natural disasters such as volcanoes, wildfires, and drought.

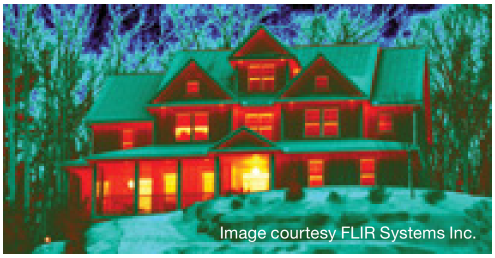
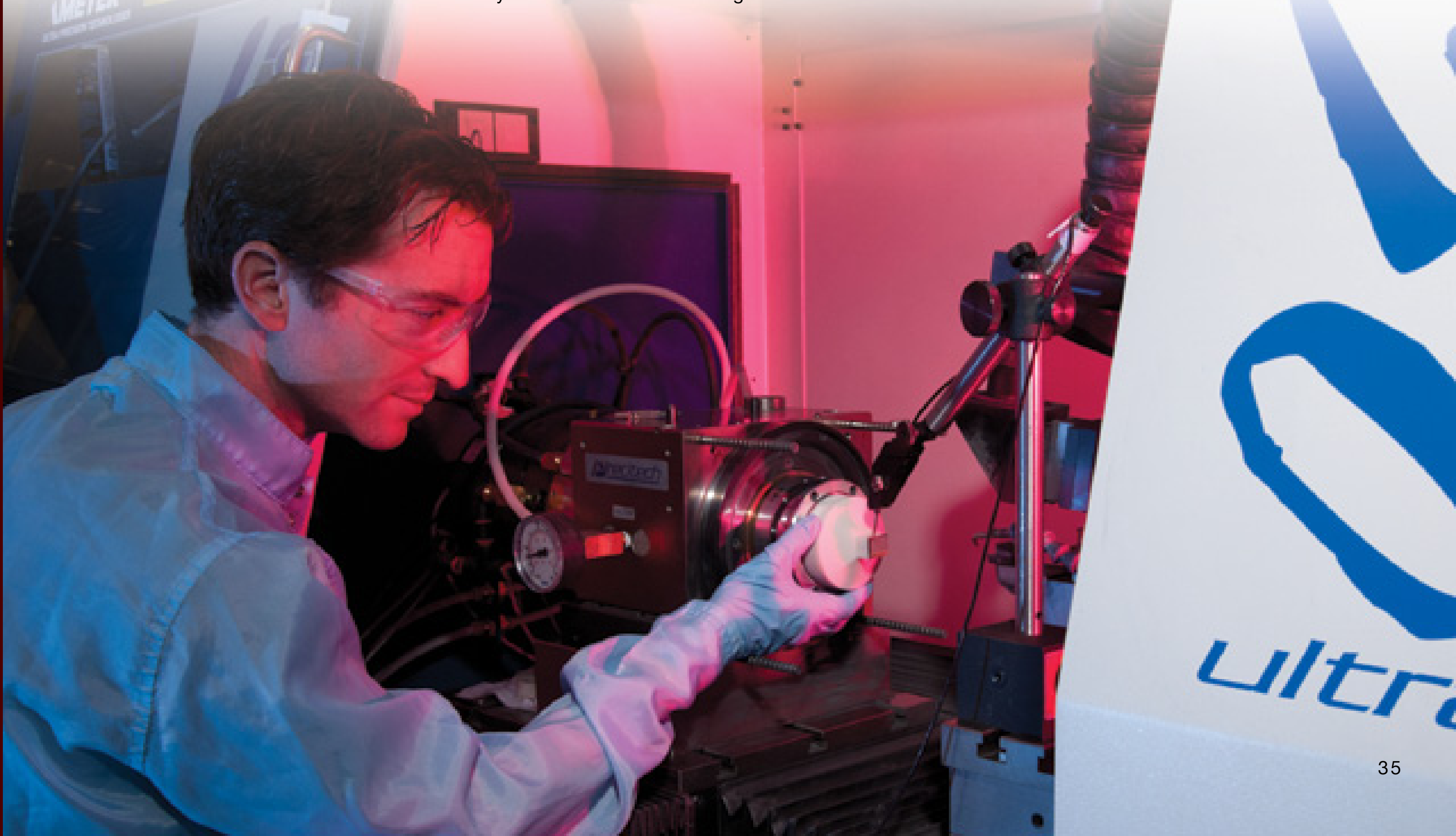


Image courtesy FLIR Systems Inc.

Above: In this infrared image of a house in wintertime, the bright areas indicate heat leaks from the house. Below: A megapixel infrared focal plane array is mounted on to the holder of diamond-point-turning (DPT) fly-cutting system. The precision DPT fly-cutting process will remove the thick GaSb substrate of BIRD focal plane arrays to avoid the thermal mismatch between the GaSb detector array and silicon read-out integrated circuit.

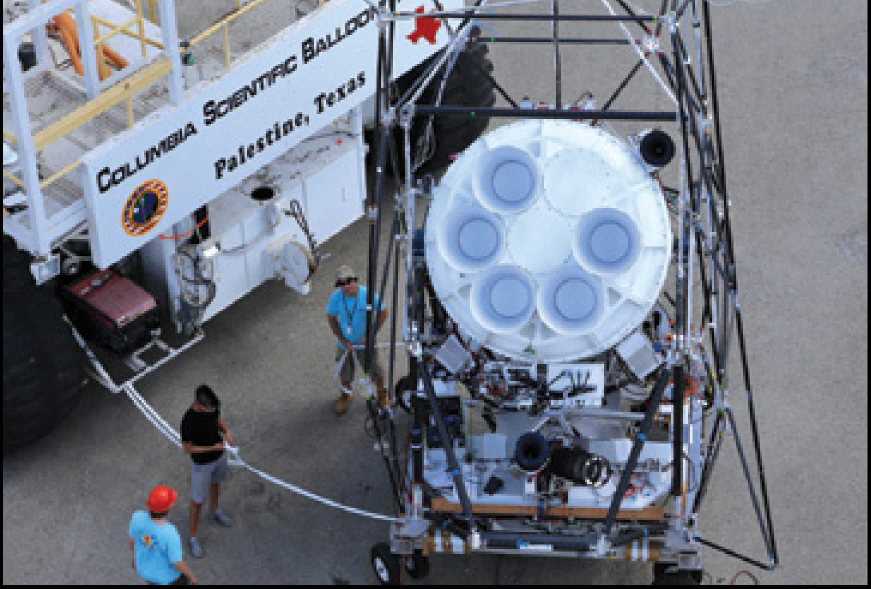


NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) is orbiting the Moon to gather details about the composition of the lunar atmosphere. On board the LADEE spacecraft is the transmitter for the Lunar Laser Communication Demonstration (LLCD), NASA's first high-rate, two-way, space laser communication technology demonstration mission. An SNSPD detector array was developed by MDL for one of the LLCD ground stations, where it demonstrated downlink communication of high-definition video at 79 megabits per second from the LADEE spacecraft. Read more about SNSPDs on page 42.

SUPERCONDUCTING MATERIALS & DEVICES

MDL researchers advance devices that detect the cosmic microwave background and the elemental composition of distant galaxies, and at home empower new telescopes.

Superconducting devices and materials researchers lead or participate in all aspects of device technology from invention, initial concept demonstration, microfabrication, and engineering development to final integration and testing in the fielded instrument and data analysis. Superconducting devices require cryogenic temperatures to operate, from millikelvin temperatures, less than 1 K from absolute zero, to liquid helium (1–4 K) and liquid nitrogen temperatures (77 K). The researchers have experience in engineering, qualifying, and testing cryogenic support structures; hybridization of microfabricated devices on low-temperature capable electronics boards; high-density, low-thermal impact cabling; and high-speed electronics. Novel, nonsuperconducting materials have also been used to create new devices that operate in higher temperatures such as the ambient environment on Mars. >>



Above: The Spider gondola being prepared for balloon launch in Palestine, Texas. Spider is a collaboration led by Professor Bill Jones at Princeton and Professor Jamie Bock at Caltech.

MDL Detectors Enable a New Probe of the Infant Universe

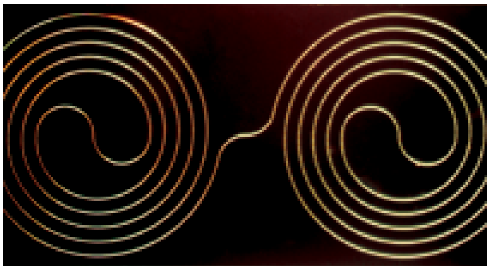
On March 17, 2014, major media outlets around the world spread the amazing news that scientists had managed to see back very nearly to the beginning of time, to 10^{-35} seconds after the Big Bang. This discovery, made using MDL-developed superconducting detectors deployed in the Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2) telescope at the South Pole, was announced by Caltech professor and JPL Senior Research Scientist Jamie Bock and his university collaborators. Their measurement of a specific polarization signal in the cosmic microwave background (CMB) is an important confirmation of key aspects of the theory of cosmic inflation and is also the first experimental indication of the connection between gravity and quantum mechanics. The same MDL detector technology is also enabling several new CMB polarization instruments, including the Keck Polarimeter Array and soon BICEP3 at the South Pole, as well as the Spider balloon experiment, which will study polarization on larger patches of sky from a balloon-borne platform.

In 2013, MDL completed and delivered focal planes for a successful test flight of Spider out of Palestine, Texas. MDL increased the optical efficiency of the arrays to above 50%, not only for Spider but also for BICEP and Keck, and also fabricated new arrays tuned for 96 GHz for the 2014 season. Similar technology is being applied in a new sensor that will be used by the TIME project to map redshifted far-infrared line emission produced by star-forming regions in the first generation of galaxies.

MDL scientists and engineers are engaged in a variety of other astrophysics projects. They include upgrades for HAWC+ (High-resolution Airborne Wide-bandwidth Camera) for the study of star formation and interstellar medium physics; development of infrared focal plane detector systems for Euclid, an ESA mission to map galaxies in the universe as a probe of dark energy; and analysis of data returned by the High-Frequency Instrument (HFI) on Planck, which has made state-of-the-art maps of the CMB also using MDL-produced detectors.

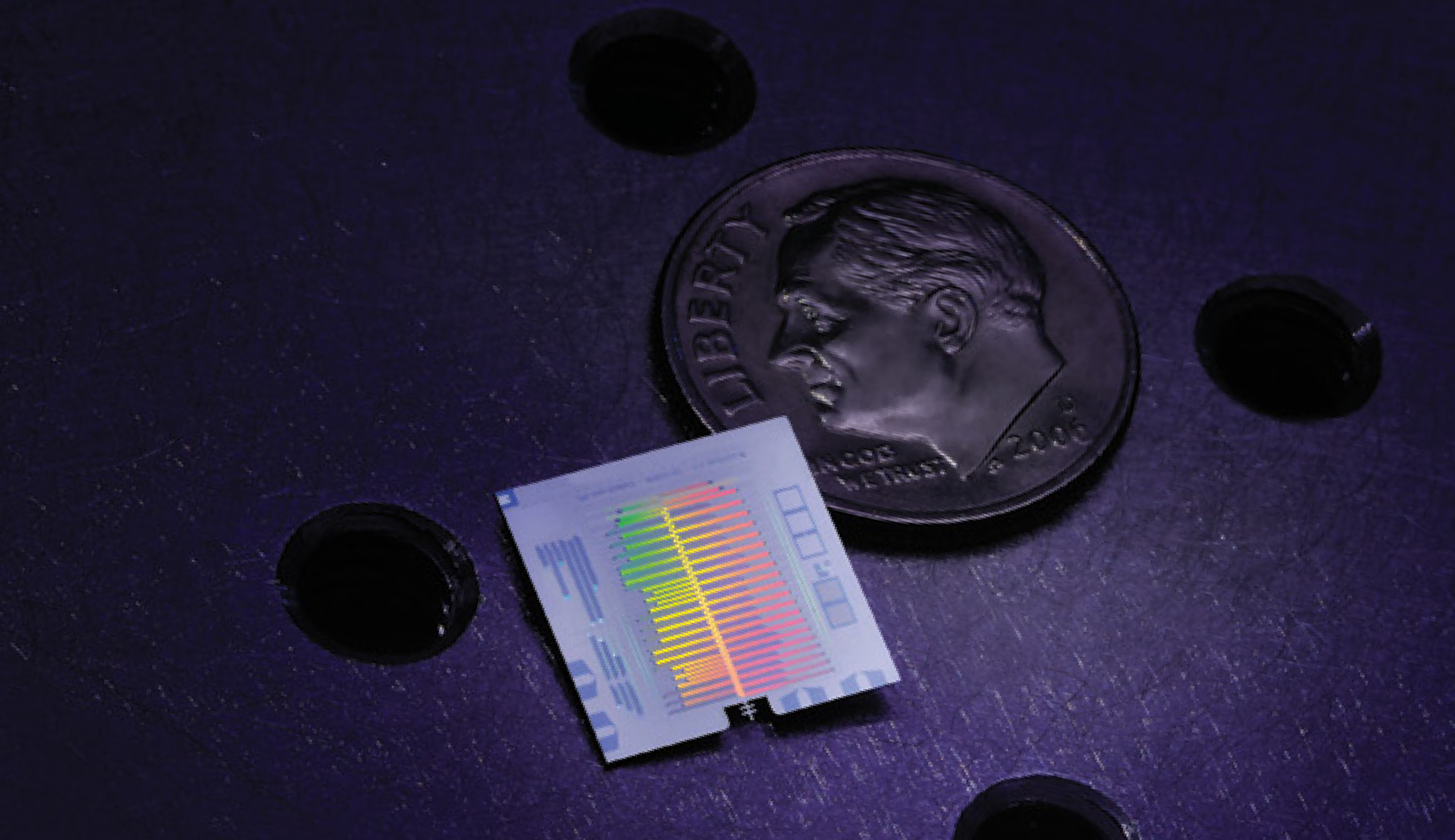
MDL's Superconducting Parametric Amplifier Continues Development Toward Testing at the Atacama Large Millimeter Array (ALMA)

First demonstrated in 2012, a breakthrough in superconducting parametric amplifier (paramp) design at JPL offers the promise of near-quantum-limited noise temperature with more than ½ octave of bandwidth for receivers operating below ~1 THz. Since 2012, the gain and noise of the paramps operating around 10 GHz have steadily improved, with single-stage amplifiers now achieving around 20 dB wideband gain with added noise of around two photons per second per Hz bandwidth. The current focus is to apply the new amplifier concept to the millimeter and submillimeter bands with near-term work focused on testing an amplifier designed for ALMA band 3 (84–116 GHz), currently under construction in northern Chile. This work will serve as a stepping-stone towards paramps working at higher frequencies in support of future NASA missions.



Above: A section of a W-band traveling-wave kinetic inductance parametric (TKIP) amplifier. It consists of a 0.15 m length of NbTiN coplanar waveguide (CPW) line arranged in double spirals. The thickness of the line is 35 nm and the center conductor and gap widths are 1 micron. Below: ALMA is an astronomical interferometer of radio telescopes in the Atacama desert of northern Chile.

Photo courtesy ALMA (ESO/NAOJ/NRAO).



Submillimeter- and Millimeter-Wave Detectors Based on MKID Arrays Achieved Three Significant Firsts in 2013

Funded by NASA Research Opportunities for Space and Earth Sciences (ROSES) grants, development and demonstrations of three focal plane detectors continued through 2013. First light occurred on a 432-element submillimeter-wave photometer, called MAKO, in April 2013 at the Caltech Submillimeter Observatory (CSO). A laboratory demonstration of a novel superconducting microstrip spectrometer, called Superspec, was performed at Caltech. In addition, detectors for the Multiwavelength Submillimeter kinetic Inductance Camera (MUSIC), a 576-pixel, 4-band millimeter-wave photometer, were completed, followed by a two-month observing campaign at the CSO in late summer.

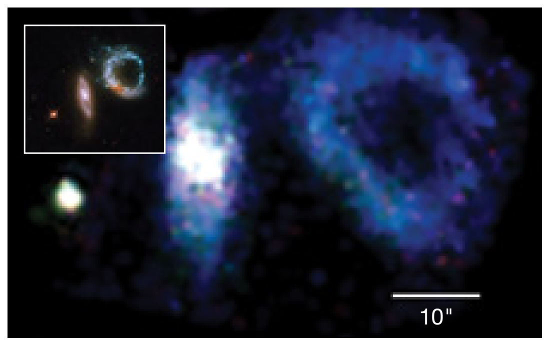
On September 26–27, all three instruments were presented at the preliminary design review for the Cerro Chajnantor Atacama Telescope (CCAT) as candidate first-light instruments. MAKO was selected and continued development of the Superspec based instrument was also advocated.

Above: A prototype single-chip spectrometer operating in the millimeter-wave regime. The millimeter-wave signal is coupled from a waveguide (not shown) through probe at the bottom of a chip and transmitted via superconducting microstrip down the center of the chip. Tuned filters along the microstrip redirect narrow bands of the radiation to individual detectors along the side of the microstrip to determine the spectral content of the original signal.

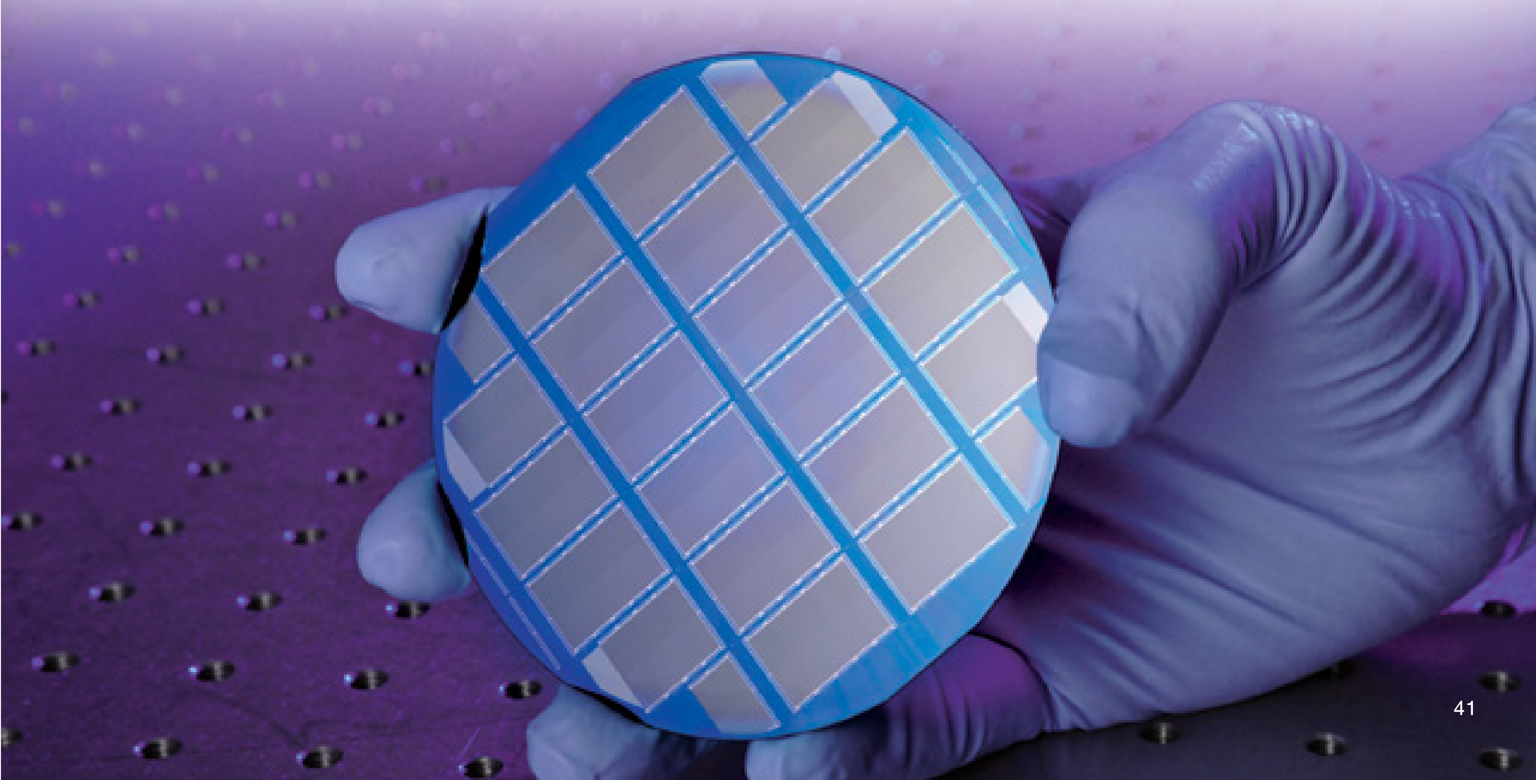
Novel Device May One Day Directly Discover and Take Spectra of Planets Around Nearby Stars

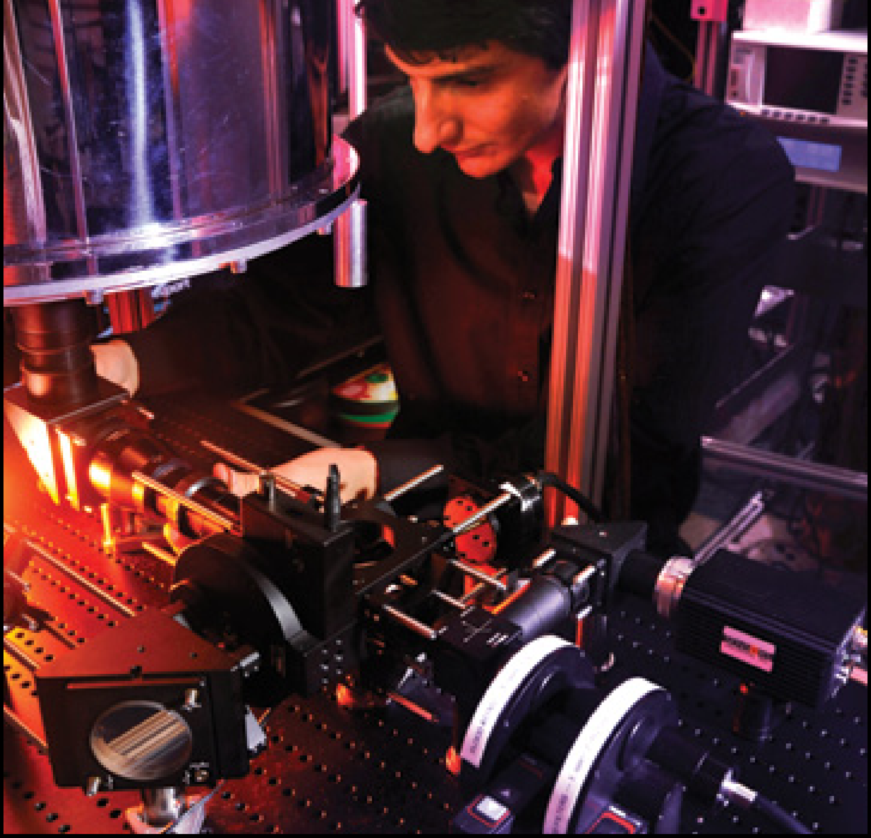
MDL is teaming with Caltech and the University of California at Santa Barbara (UCSB) to develop ultraviolet, optical, and near-infrared focal plane arrays based on optical lumped element (OLE) microwave kinetic inductance detectors (MKIDs). These OLE MKIDs, used to measure energy across the electromagnetic spectrum, are being developed for use in a new hyperspectral imaging device for Professor Ben Mazin of UCSB.

This novel device, called ARray Camera for Optical to Near-infrared Spectrophotometry (ARCONS) is a unique imaging focal plane detector technology where each pixel acts as a spectrometer to differentiate ultraviolet, optical, and near-IR light. ARCONS, built for ground-based telescopes, will allow researchers to observe incoming light far more efficiently than conventional CCDs as well as track quickly changing deep space phenomena such as optical pulsars and planetary transits.



Above: This mosaic of interacting galaxies was taken with ARCONS. The inset shows the same field of view from the Hubble Space Telescope. Unlike Hubble's image, the ARCONS images were taken without multiple exposures through color filters — each pixel contains an instantaneous spectrum within it. Below: A wafer of several of the first 10,000-pixel near-IR MKID arrays for the planet-finding instrument named Dark-speckle Near-IR Energy-resolved Superconducting Spectrometer (DARKNESS).





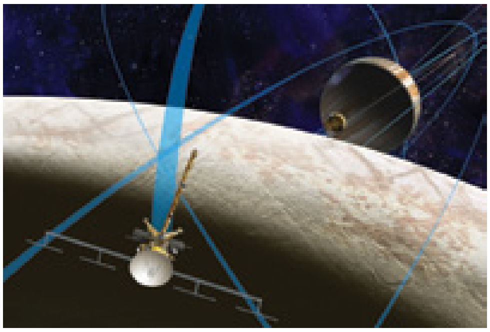
Above: The free-space optical coupling is adjusted for a 64-element SNSPD module for NASA's Deep Space Optical Communication project. MDL has fabricated the largest active-area SNSPD array to date, and has been the first to demonstrate optical communication with free-space coupled SNSPD arrays suitable for coupling to large telescope apertures.

Superconducting Nanowire Single-Photon Detectors Study Marks Three Milestones in 2013

The superconducting nanowire single-photon detector (SNSPD) projects made three significant achievements in 2013. A ground receiver for the lunar laser communication demonstration (LLCD) based on an MDL-fabricated 12-pixel SNSPD array was developed in collaboration with JPL's optical communication group. This receiver was fielded on the Optical Communications Telescope Laboratory (OCTL) telescope at JPL's Table Mountain Facility, and used to successfully downlink error-free data from lunar orbit at 79 Mbps. In addition, two different versions of free-space coupled SNSPD arrays with photon collection areas 8 times larger than the previous state of the art were demonstrated with useful optical efficiency. The arrays were used for proof-of-concept advanced communication experiments under NASA's Deep Space Optical Communication project and DARPA's Information in a Photon program. MDL's tungsten silicide SNSPDs have demonstrated record-breaking efficiency (> 90%) in the infrared, with 150 ps timing jitter, 40 ns reset time, and subhertz intrinsic dark counts. They may be useful for a variety of future applications such as lidar, quantum communications, and high-time-resolution astrophysics.

Thermopile Detector Arrays Baselined for Thermal Imager on Europa Clipper

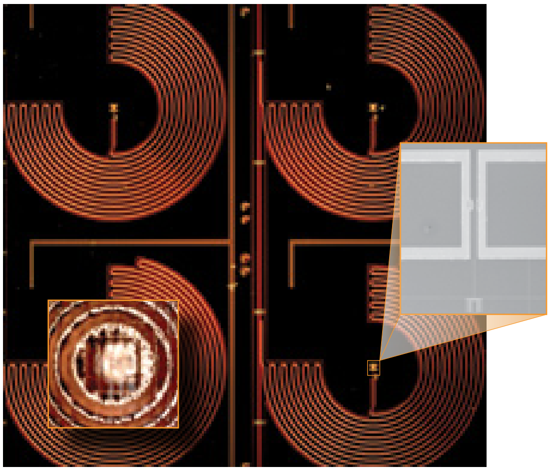
MDL-developed thermopile detector arrays are the baseline detector for JPL's thermal imager on Europa Clipper. Other applications for thermopiles developed in 2013 include a far-IR spectrometer concept for a CubeSat, the follow-on mission to Earth Clouds and the Earth's Radiant Energy System (CERES) called Radiation Budget Instrument (RBI), and a proposed New Frontier mission Trojan Tour and Rendezvous (TTR). A pressure sensor using an MDL thermopile with a sensitivity of ~0.1 microPa was also demonstrated in the laboratory as a backup sensor for NASA's InSight mission.



Above: Europa Clipper is a concept under study by NASA that would conduct detailed reconnaissance of Jupiter's moon Europa and would investigate whether the icy moon could harbor conditions suitable for life.

MDL Quantum Capacitance Detector Achieves New World Record Noise Performance

The quantum capacitance detector (QCD) achieved a new world record noise performance, showing photon shot noise limited performance for 200 microns wavelength photon or with noise equivalent power (NEP) as low as 10^{-21}W/Hz$^{1/2}$ for the lowest photon fluxes measured. A new four-year NASA grant was awarded to continue development and infuse the QCD into instrument concepts.



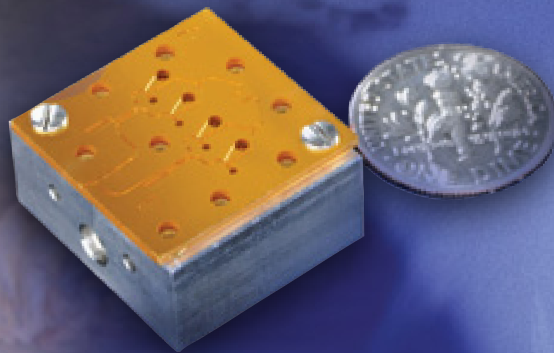
Above: Four QCD pixels with one element of the Fresnel lens array shown superimposed on one of the pixels. The lens array is glued to the back of the detectors, which are backside illuminated. A meandering coplanar waveguide feedline is capacitively coupled to each CPW half-wave resonator (the spiral structures). The detail shows the double dipole antennas at the opposite end of the resonators.

A portion of western Eistla Regio is displayed in this view of the surface of Venus. Gula Mons, a 3-kilometer-high volcano, is visible in the image. MDL has been funded by NASA to develop a state-of-the-art submillimeter-wave radiometer/spectrometer for orbiter missions to Mars, Venus, Titan, and the Galilean moons. It will allow a large number of compounds — such as water, hydrogen sulfide, nitrogen dioxide, and methane, among others — to be detected at concentrations below a part per billion from orbit. Read more on page 46.

SUBMILLIMETER-WAVE ADVANCED TECHNOLOGIES

MDL capabilities allow us to peer into the early universe, keep us secure at home, and ensure future missions to 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. >>



Compact Submillimeter-Wave Instruments for Planetary Exploration

NASA has funded development of a super-compact submillimeter-wave instrument for planetary exploration. Using newly developed silicon micromachining technology that enables a low-mass and highly integrated receiver, the Planetary Instrument for Submillimeter-wave Surface and Atmospheric Reconnaissance and Research in Orbit (PISSARRO) will provide a state-of-the-art submillimeter-wave radiometer/spectrometer for orbiter missions to Mars, Venus, Titan, and the Galilean moons. PISSARRO will allow a large number of chemical species, such as water, NO_2, N_2O, NH_3, SO_2, H_2S, CH_4, and HCN, among others, to be detected at concentrations below a part per billion.

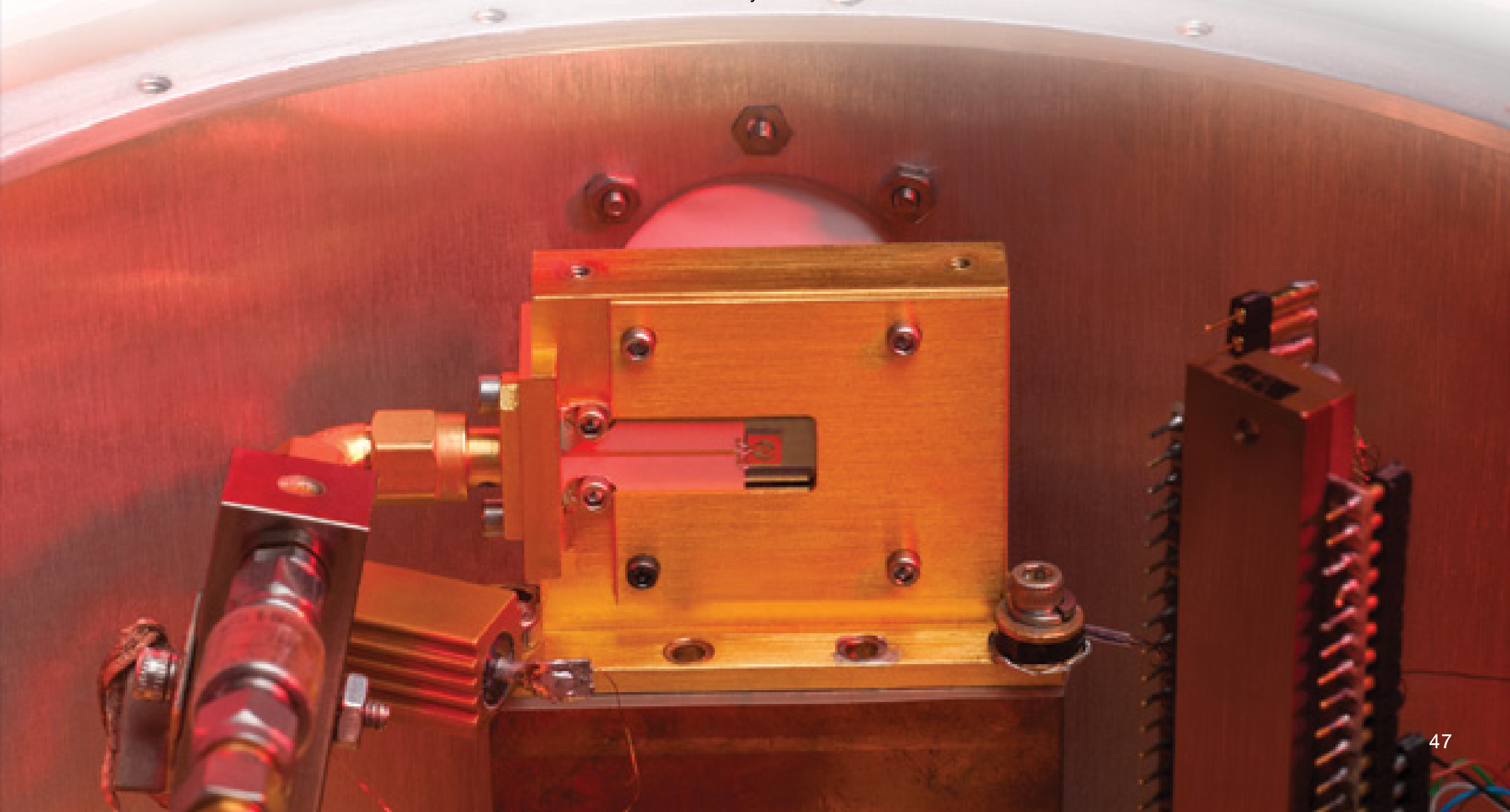
In exploring planets and their moons from orbit, PISSARRO will gather data on the thermal structure, dynamics, and composition of planetary atmospheres and surfaces. In radiometer mode, the instrument will measure the polarized thermal emission, revealing aspects of its chemical composition and physical state. As a spectrometer, PISSARRO will investigate the sources and sinks of trace gases and globally characterize the atmosphere with high spectral, spatial, and temporal resolution uniquely available through submillimeter-wave spectroscopy. It will also measure wind speeds, temperature, pressure, and key constituent concentrations in the planetary atmospheres with a higher precision than any other available technology.

This page: Artist's concept of a plume of water vapor thought to be ejected off the icy surface of Jupiter's moon Europa. Data from NASA's Hubble Space Telescope have led scientists to calculate that plumes may rise up to 201 kilometers. Above: The silicon-micromachined front-end of the PISSARRO instrument. It houses eight gallium arsenide devices along with the supporting waveguide circuitry to reduce the mass and volume while increasing the measurement capabilities of the instrument.

Novel High-T_c Material for High Sensitivity Microbolometers May Enable a Mechanically Cryocooled Instrument in Space

MDL is pursuing the development of a novel hot-electron bolometer (HEB) mixer utilizing a high-T_c MgB_2 superconductor. The aim of this work is to make possible the mechanical cryocooling of an instrument in space and to increase the intermediate frequency bandwidth by a factor of three compared to current NbN HEB mixers. The novel material will allow for reaching the intermediate frequency of 8 GHz or higher and for operating the mixer at 25 K or above where mechanical space-qualified cryocoolers are readily available. Achieving these technical objectives will significantly advance the state of the art of heterodyne instrumentation for high-resolution terahertz spectroscopy. THz antenna-coupled devices have been fabricated at MDL, and future developments will explore submicron-size devices as well as the devices on thin membrane for integration with THz waveguide arrays.

Above: The spiral structure in the middle of the mixer chip is a planar THz antenna coupling the HEB mixer to radiation. The mixer device has micron lateral size not visible at this magnification. Below: A laboratory cryogenic system for testing, where the mixer chip is mounted in a special quasioptical block containing silicon lens for focusing the THz beam onto the antenna and electrical bias and read-out circuitry.

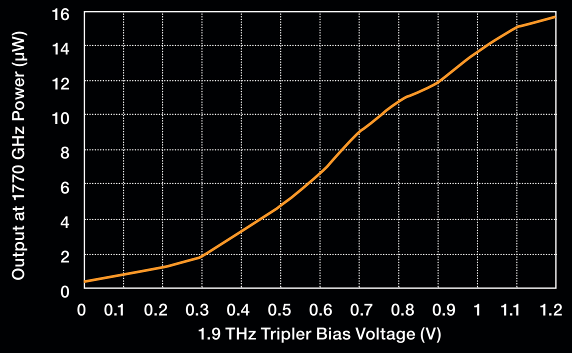


Above: Artist's impression of the distribution of molecular gas across the plane of the Milky Way.

Development of a Bias-Able 1.9 THz Source for the Study of Galaxy and Star Formation

The Heterodyne Instrument for the Far-Infrared (HIFI) on board ESA's Herschel spacecraft is a very high-resolution heterodyne spectrometer that provides extremely detailed spectra of the atoms and molecules that make up stars and galaxies. In 2013, data from HIFI indicated that the C+ molecule is abundant in our universe, revealing there is more molecular gas for the formation of new stars in our own Milky Way galaxy than previously estimated.

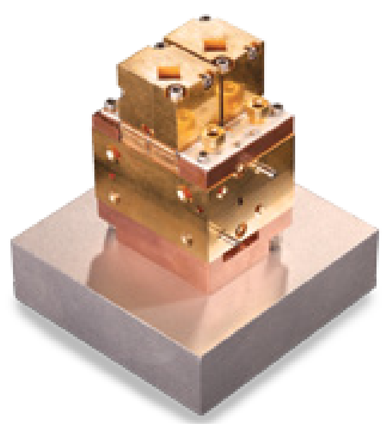
Critical to the HIFI instrument are MDL-developed Schottky and superconductor–insulator–superconductor (SIS) devices. MDL is currently working on next-generation devices and technologies to enable multipixel arrays to increase science throughput. In 2013, MDL designed, fabricated, and demonstrated a 1.9-THz tripler with biasing capability. The measured results below show that the output power at 1.9 THz can be controlled with bias, an important development for multipixel receiver architectures for future missions.



Artwork above courtesy ESA - C. Carreau.

Demonstration of a 4-Pixel, 340-GHz Imaging Radar Shows Potential for Both National Security and Scientific Applications

In 2013, MDL scientists perfected a silicon micromachining process for fabricating the waveguide components of an integrated 340-GHz radar transceiver array. The effort culminated in the successful demonstration of an inch-sized two-element array unit cell *(shown right)* that contains four 120-GHz amplifiers, four 340-GHz triplers, two 340-GHz mixers, and two waveguide hybrid couplers. This represents a three orders-of-magnitude reduction in volume over previous state of the art submillimeter-wave device packaging technology, and is a highly promising approach for fabricating complex waveguide structures at much lower costs than in the past. The silicon-based array may lead to video-rate speeds for JPL's personnel screening imaging radar, as well as new measurement possibilities for planetary remote-sensing applications.



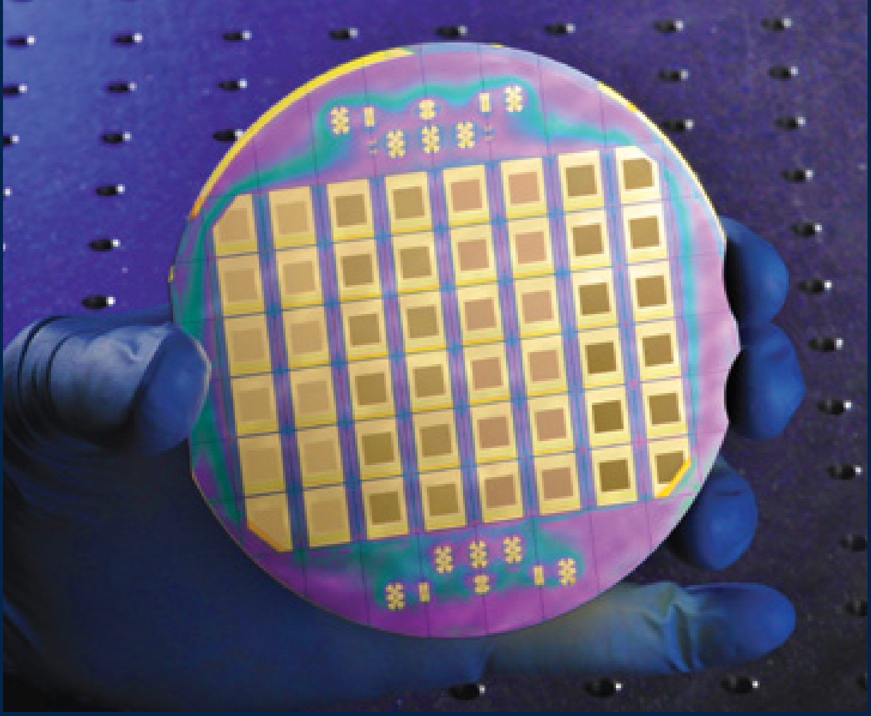
Above: JPL's integrated two-element 340-GHz radar transceiver that relies on a silicon micromachining process developed by MDL scientists. Below: Passengers are seen travelling through an airport. MDL is working on technologies that may provide instant detection of concealed threats in large moving crowds such as these.

View towards an oil rig from the coast of Mobile, Alabama. Extreme environment sensors and electronics are highly useful for commercial applications, including the oil and gas, automotive, and geothermal industries. MDL is developing components that are deployable down hole 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, keeping the production environmentally responsible. Read more on page 54.

NANO & 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, the Department of Defense, 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. In recent times, process optimization to achieve repeatability and robustness of new devices developed to address customer needs has taken a central role. This has started new research activities in hybrid micro assembly, custom packaging of integrated micro and nano components, and automation of postprocessing operations. >>



Above: Multilayer, micromachined high-temperature capacitors producing designed values over a range of tens of nF to hundreds of nF.

Advanced High-Temperature-Tolerant Component Technologies for Oil and Gas Applications

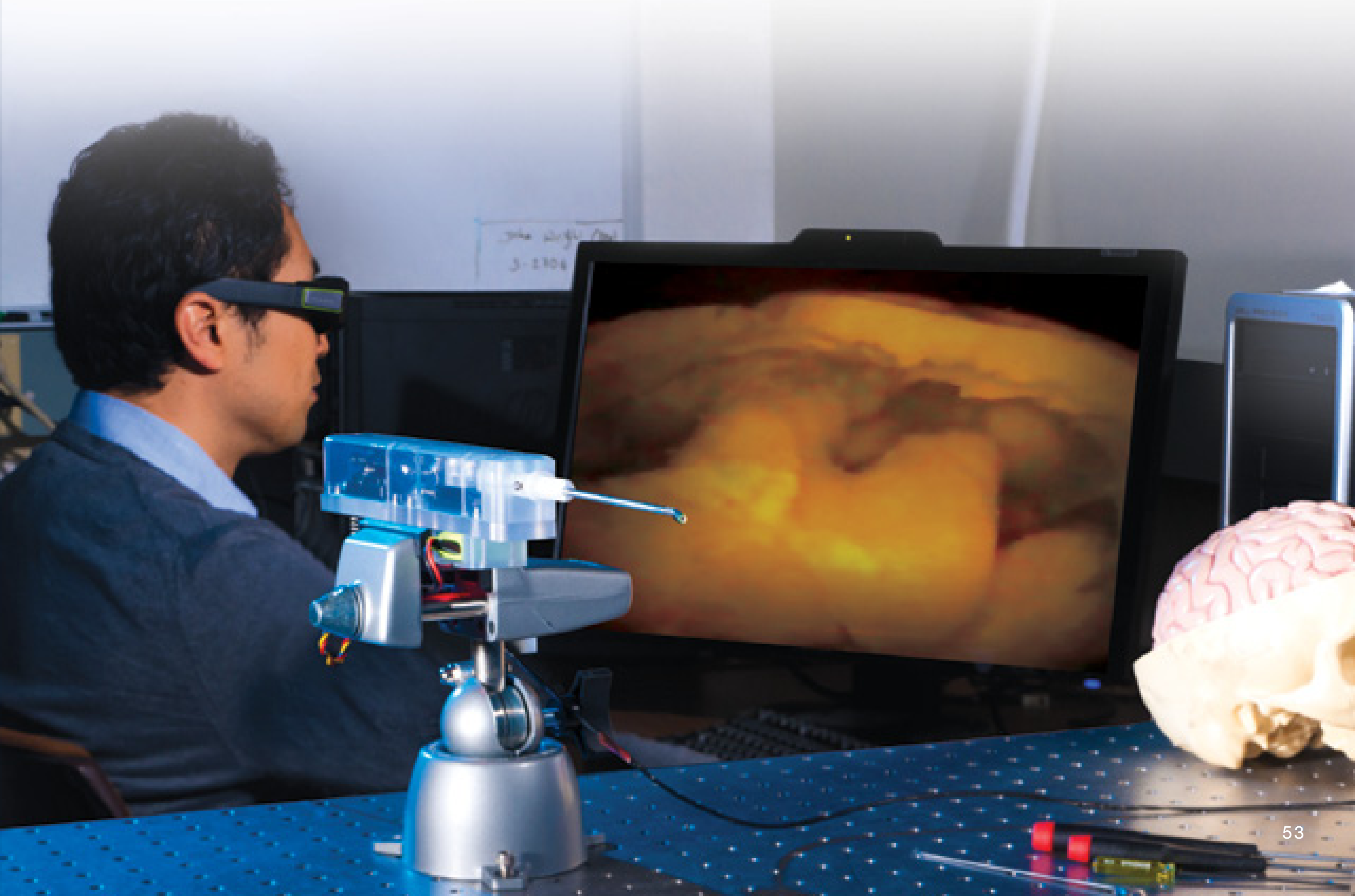
The extreme-environment sensors and electronics expertise that exists within MDL has led to development projects with the oil and gas industries to create novel components that are deployable down hole for prolonged and uninterrupted operation.

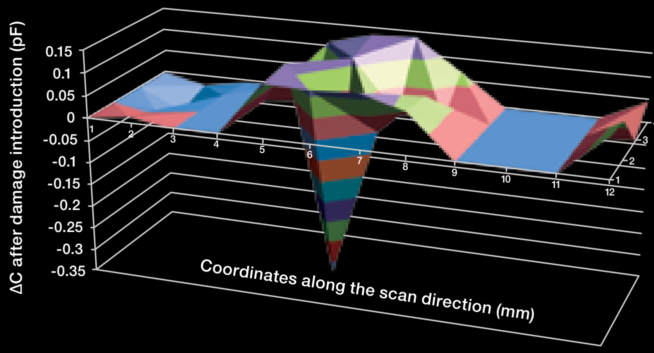
JPL continues to develop high-temperature-tolerant components such as carbon nanotube (CNT)–based vacuum electronic devices, and silicon micromachining-based capacitors. The process of development involves hybrid microassembly and improved vacuum packaging technologies. Using a manual hybrid assembly technique, several active devices were fabricated and tested in traditional vacuum packages. Such vacuum-packaged CNT diodes and triodes revealed that the hybrid microassembly process is producing devices that are approaching field deployment specification for oil and gas applications. Multilayer, micromachined capacitors have been made ready to be field-tested as well. Recently, these components were tested and verified with developments now proceeding towards automated microassembly, chip-scale vacuum packaging, and process yield enhancement stages.

Novel Tool Produces High-Definition 3D Images for Minimally Invasive Brain Surgery

JPL delivered a functional prototype of 3D-MARVEL (Multi-Angle Rear-Viewing Endoscopic) to the Skull Base Institute in 2013. This unique tool incorporates possibly the world's smallest HD-capable stereo camera at its tip, which can be steered from side-to-side affording a panoramic view of the surgical environment. It was developed for minimally invasive neurosurgery. The outer diameter of the endoscope is less than 4 mm, with its camera being less than 3 mm in diameter. This single-lens system employs dual apertures with complementary multiband pass filters to create two time-multiplexed viewpoints of an object to produce stereo images. A new light source was developed to produce continuously cycling illumination bands to be incident upon the object of interest. A tightly packed fiber optic array transports these illumination bands to the front of the camera. A CMOS image sensor captures stereo images. The stereo camera is welded to a bending section to enable side-to-side steering (designed for ±60°) using a cable-pulley arrangement that is controlled by a JPL-designed actuation system.

Below: Photograph of the 3D-MARVEL functioning laboratory prototype delivered to the Skull Base Institute in 2013.





MDL Is Developing Structural Defect Detection Technology with Improved Sensing Capability for NASA

Damage detection in structural materials is difficult, yet critical to avoid catastrophic failure. No single damage-detection technology can cover the various defect types (delamination, fiber fracture, matrix crack), or conditions (visibility, crack length size) in aerospace structures. These defect states will become even more complex in novel composites that include nano/microparticle reinforcement.

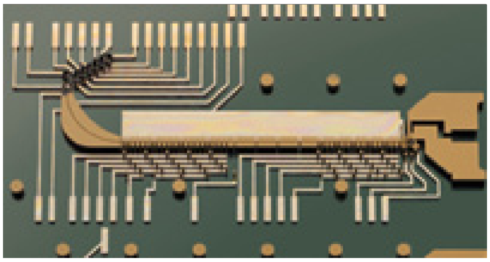
JPL is developing a thin-film capacitance, sensor-based, structural defect detection technology with improved sensing capability for NASA. Thin-film sensors are integrated as the part of the structure; the defect in the structure directly alters the sensing layer's capacitance, allowing full-coverage sensing capability of small defects independent of defect size, orientation, or location. Such sensors have been successfully tested on carbon-fiber reinforced plastic (CFRP) as a common aerospace structural material, and carbon nanotube (CNT) prepreg as a novel nano-engineered material.

Above: 3D map of sensor measurement indicating location of damage. Below: The Canadarm2, aboard the International Space Station, is capable of maneuvering payloads as massive as 116,000 kilograms, equivalent to a fully loaded bus. MDL is developing damage-detection devices that will help avoid potential failures in aerospace structures.

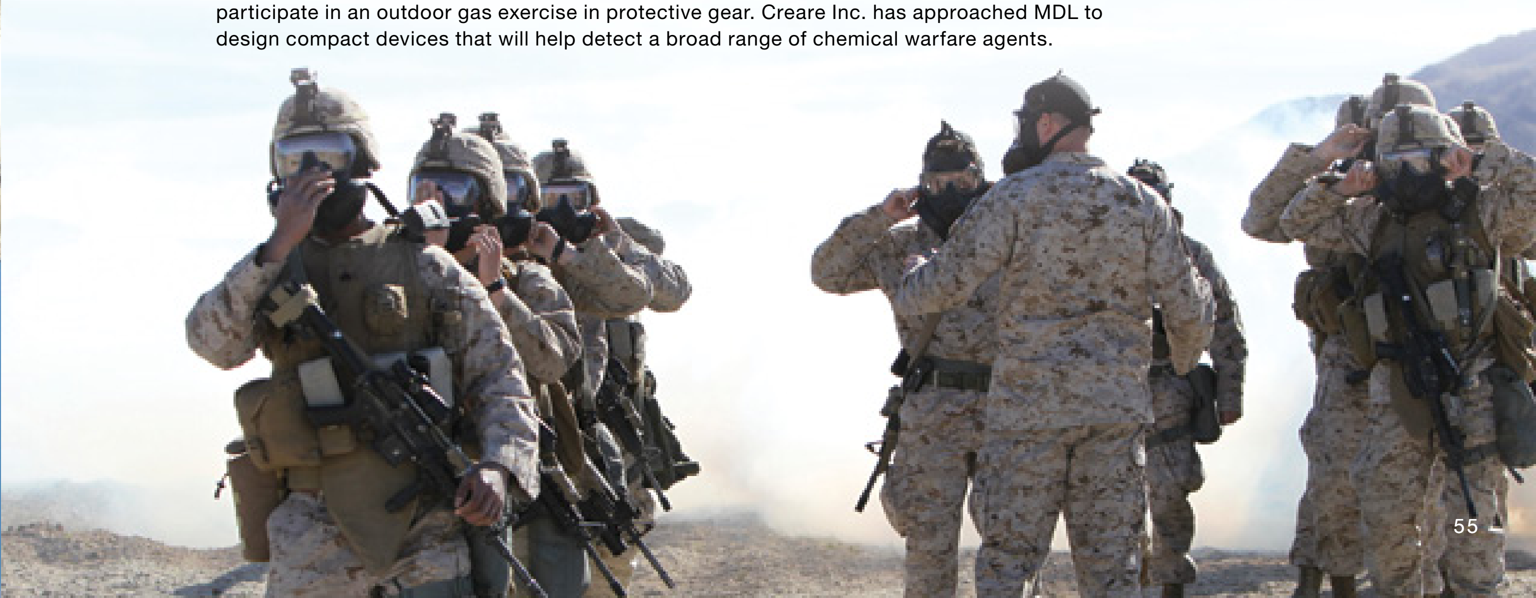
Partnership to Produce Chip-Scale Mass Spectrometers for Defense and Other Applications

Creare Inc. in New Hampshire has formed a collaborative effort with JPL in microtechnology development on a number of Department of Defense–funded technologies, including a portable chip-scale mass spectrometer for in situ detection of chemical warfare agents. On this chip are carbon nanotube (CNT)–based gas ionizers, charged-particle focusing optics, a mass filter, an energy filter, and an electron multiplier detector. CNT emitters are valuable because they offer low-voltage ionization, which simplifies the electronics and enables a more compact design. Mass filter electrodes were designed to minimize stray fields and maximize resolution. The mass filter, together with the energy filter, enables precision determination of the charge-to-mass ratio (e/m) of ionized gas molecules. The electron multiplier amplifies the ion current signal to maximize sensitivity.

The out-of-plane height of JPL's mass spectrometer chip is extreme (800 micrometers) by microfabrication standards, and ensures greater gas throughput for rapid chemical analysis; this, together with the four-wafer construction of the device, demonstrates a new level of capability for complex miniaturization and system integration at MDL. This chip, integrated with Creare's miniature turbo-molecular pump, will be a truly portable instrument and the world's smallest mass spectrometer system. While designed for the detection of chemical warfare agents, it can be modified to detect molecular species of interest to NASA, such as CO_2 monitoring on the International Space Station, or the detection of CH_4 and other organics for life detection signatures.



Above: JPL's mass spectrometer chip integrates the sample preparation, filter, and detector elements of a traditional mass spectrometer system, all on a single chip. Below: Marines participate in an outdoor gas exercise in protective gear. Creare Inc. has approached MDL to design compact devices that will help detect a broad range of chemical warfare agents.



Three nanosatellites, known as CubeSats, are seen deployed from the International Space Station in October 2012. CubeSats offer the benefit of low-risk, cost-effective alternatives for exploratory missions and technology demonstrations, but precision pointing and propulsion capabilities are extremely limited on these small spacecraft. MDL is currently developing an advanced micropropulsion thruster for spacecraft to enable missions to the asteroid belt and Mars with these shoe-box-sized spacecraft.

MICROFLUIDIC ELECTROSPRAY PROPULSION

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

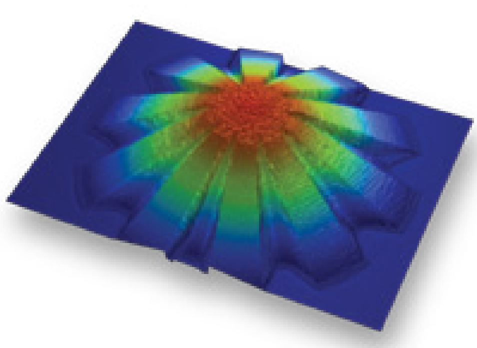
The microfabrication requirements of electrospray thruster components surpass traditional microfabrication techniques. Using state-of-the-art fabrication tools at MDL, engineers are developing new techniques to fabricate the next generation of components that will bring new small and large spacecraft mission capabilities to fully utilize the capabilities of advanced spacecraft instruments. The 3D microfabrication technique, developed at MDL, has enabled the fabrication of scalable electrospray thruster needle arrays with integrated capillary-force-driven feed systems to spray indium charged particles to generate micronewtons to millinewtons of thrust at very high efficiency and specific impulse to enable interplanetary missions. >>

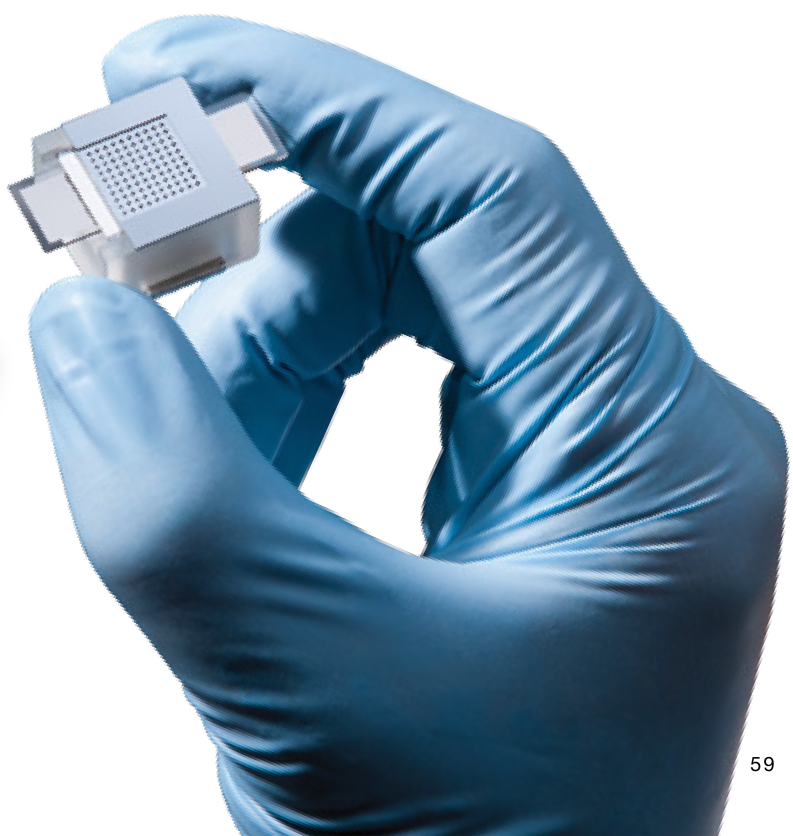
An MDL researcher programs an etching process on MDL's newly installed plasma-therm Deep Silicon Etcher to fabricate arrays of complex 3D silicon needles with micron-scale tolerances.

Microfluidic Electrospray Propulsion May Allow Microspacecraft to Fly to Mars or the Asteroid Belt

Small spacecraft currently under development in the 3- to 50-kilogram mass range have very limited delta-V capability. Microfluidic electrospray propulsion (MEP) technology, currently under development at JPL, may one day enable delta-Vs of thousands of meters/second and the precision pointing of small spacecraft for planetary missions and missions to explore asteroids. The scalable, highly integrated MEP assembly has a dry mass less than 10 grams and is under development for 20–100 micronewtons of thrust. Its technology comprises an electrospray thruster with microfabricated components that include a silicon chip etched with micron-scale electrospray needles, heater chip, extraction electrode chip, and propellant reservoir. The propellant, indium metal, is stored as a solid and then heated to melt, flow, and spray. The feed system has no pressurized reservoir or valves. Instead, the propellant is capillary force driven from the reservoir, through the emitter array chip and to the tip of the emitters. High-electric fields applied between the emitters and the extractor electrode accelerate the indium charged particles to create thrust.

In 2013, MDL continued to refine fabrication techniques for the components of the MEP thruster. The process under development for creating the emitter array chips includes a grayscale lithography for 3D-micro rapid prototyping of complex silicon needle configurations with micron-scale precision. MDL also fabricated MEP thruster pyrex heater chips and silicon extraction grid chips. They were tested with the emitter array chips in the MEP thruster prototype assembly in the Microthrust Propulsion Laboratory (MPL) with over 10 hours of continuous operation. Technology development now continues to improving emitter needle array fabrication uniformity, and integration of axial grooves to support the capillary force driven flow of indium from a propellant reservoir through the emitter chip and to the tips of the emitter needles.





Above: A 3D oxide mask that is used to fabricate the complex needle configurations needed for the emitter array chips. Right: A MEP thruster prototype assembly.

Due to mercury levels, eating fish from East Fork Poplar Creek is not recommended. It is on a state list of impaired waterways due to contaminants from buildings at the Y-12 National Security Complex used to make nuclear weapons in the 1950s and 60s. Flowing through Oak Ridge, Tennessee, it is thought to affect fish in other connected water bodies. The creek is currently a test bed for studies of mercury, fish, and the roles of bacteria in increasing or decreasing methylmercury concentrations in water. In support of studies such as this, MDL is working with Los Gatos Research to develop portable devices that will help aid in on-site mercury monitoring and speciation. More on page 62.

IN SITU INSTRUMENTS

As planetary and Earth studies evolve, increased emphasis lies on the ability to perform analyses remotely and robotically.

NASA continues to develop and deploy new physical, chemical, and geological instruments on robotic platforms. In particular, the Mars Exploration Program is conducting surface investigations for evidence of aqueous habitats with future missions planned to target the search for organic compounds. The ultimate goal is the discovery of signs of the presence of extant or extinct life outside of our home planet. The kind and quality of data needed to support these ambitious goals could be met by returning samples from Mars and other planetary bodies for detailed analysis in terrestrial laboratories. The staggering cost of sample return missions has led to the need to conduct careful analytical experiments remotely and robotically. In response, MDL has embarked on a number of instrument developments ranging from critical optical components, through specific single experiment instruments, to sophisticated integrated systems that execute a complete experiment from sample introduction to analysis and data return. As development continues, these technologies show promise for Earth science applications as well, such as environmental monitoring and point-of-care testing. >>

Above: With partner Los Gatos Research, MDL researchers are developing portable microchip analysis systems, such as the first-generation Chemical Laptop, that are portable, battery powered, and can be taken into the field or laboratory for chemical analysis on site.

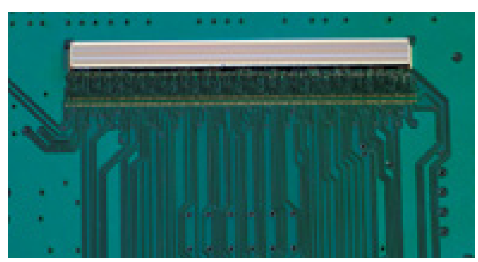
Microfluidic Technology Holds the Promise of Portable Chemical Analyses

Microfluidic technology holds the promise of portable chemical analyses, bringing the lab to the sample instead of the sample to lab. This aspect of lab-on-a-chip systems is particularly relevant for astrobiology studies where in situ analyses on extraterrestrial samples are necessary. However, this technology is also extremely important for terrestrial applications such as environmental monitoring and point-of-care testing. While the primary focus at MDL has been the implementation of microfluidic technology for astrobiology studies, it has recently expanded to environmental applications as well, through an ongoing collaboration with Los Gatos Research (LGR) for both of these applications.

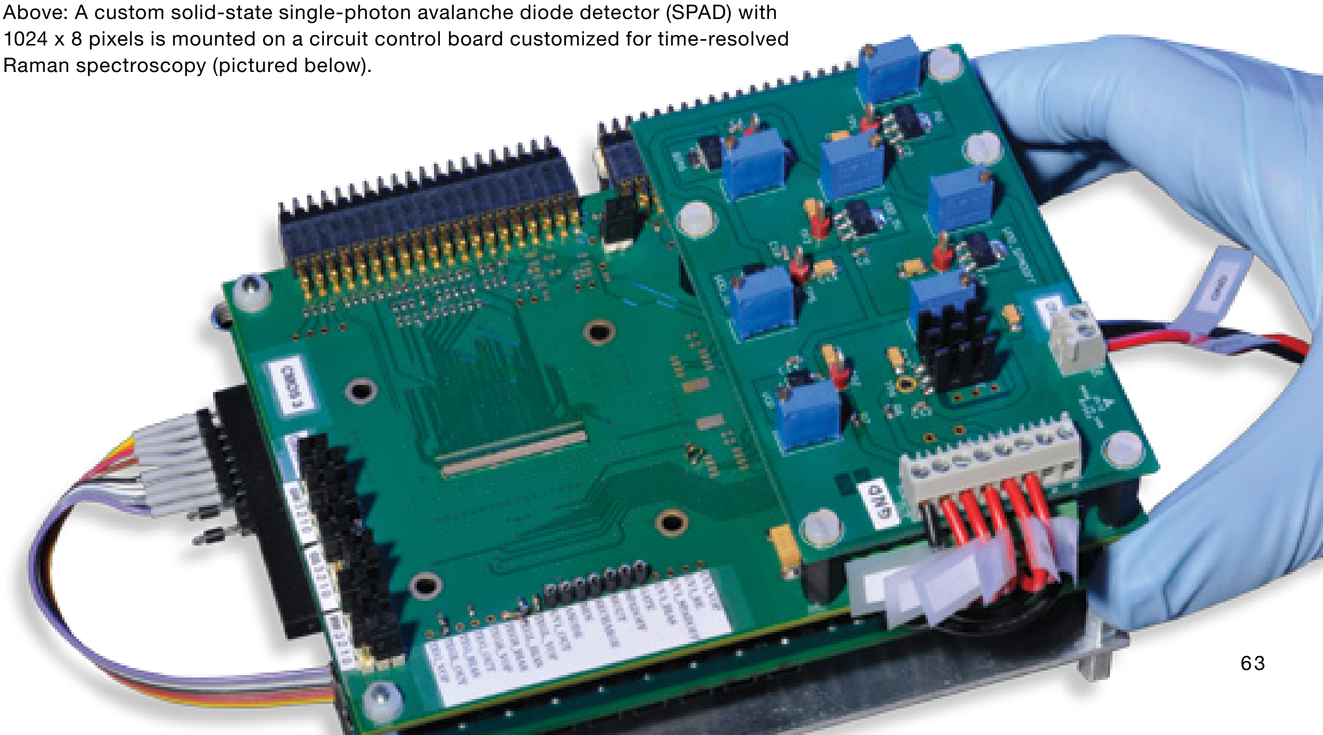
Microfabrication technologies presently allow for the fabrication of microchips that require only small volumes of sample and reagents (nL to µL). However, these devices are generally operated by relatively large instrumentation external to the microchip, which makes the overall system large and confined to a laboratory. In order to develop a truly useful lab-on-a-chip system for both terrestrial or extraterrestrial applications, the entire instrument, not just the microfluidic portion, needs to be miniaturized to make it fully portable. To that end, scientists at MDL invented and patented the Chemical Laptop in 2010. This was the beginning of the collaborative relationship with LGR. The Chemical Laptop is the first portable, reprogrammable, battery-operated, microchip capillary electrophoresis system. The first prototype of this instrument was built at LGR with NASA Small Business Innovation Research funding and delivered to JPL in May 2013. As the current unit continues testing at MDL, a second prototype (Chemical Laptop 2.0) is in development through this continuing collaboration with LGR.

Time-Resolved Raman Spectroscopy for Planetary Surface Exploration

Raman spectroscopy has been steadily gaining support as a means for using laser spectroscopy to identify mineral phases and their composition as well as organic compounds present within the mineral matrices. Raman spectroscopy has also been identified by the community as a feasible means for pre-selection of samples on Mars for subsequent return to Earth. MDL is developing a next-generation instrument that builds on the widely used 532-nm Raman technique to provide a means for performing Raman spectroscopy without the background noise that is often generated by fluorescence of minerals and organics. Microscopic Raman spectroscopy with a laser spot size smaller than the grains of interest can provide surface mapping of mineralogy while preserving morphology. A very small laser spot size (~1 μm) is often necessary to identify minor phases that are often of greater interest than the matrix phases. In addition to the difficulties that can be posed by fine-grained material, fluorescence interference from the very same material is often problematic. This is particularly true for many of the minerals of interest that form in environments of aqueous alteration and can be highly fluorescent. Time-resolved laser spectroscopy is used to eliminate fluorescence interference that can often make it difficult or impossible to obtain Raman spectra. The most significant advance leading to the feasibility of a compact time-resolved Raman spectrometer is the development of a custom solid-state detector capable of subnanosecond time resolution.



Above: A custom solid-state single-photon avalanche diode detector (SPAD) with 1024 x 8 pixels is mounted on a circuit control board customized for time-resolved Raman spectroscopy (pictured below).



An MDL researcher programs a recipe to deposit photoresist onto a wafer on MDL's new SolarSemi MC204 Microcluster Spin Coating System.

INFRASTRUCTURE & CAPABILITIES

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 by the Central Processing and MDL Support Group, which also maintains a small staff of processing personnel for specialized processing support. This group manages, coordinates, and provides direct services in maintaining the building infrastructure and equipment, including life safety systems for safety assurance. >>

In 2013, MDL continued to invest in new capabilities, as well as renew and upgrade existing capabilities:

ETCHING

Plasmatherm Versaline VLN-LL-DSE Deep Silicon Etcher (DSE/DRIE). This major acquisition (pictured on pages 58 and 69) upgrades existing capabilities in Deep Trench Reactive Ion Etching (DRIE). It will provide an enhanced deep silicon etching capability with linear and nonlinear process parameter morphing on larger (150-mm-diameter) wafers. The system can achieve high aspect ratios (>50:1); minimum etched silicon sidewall tilt (90° ±0.5°); excellent etched depth uniformity (at least ±2% across a 150-mm wafer); high material etch selectivity (for Si:Photoresist: >100:1 with aspect ratios <10:1 and > 50:1 for aspect ratios >10:1; and for Si:SiO_2: >200:1 for aspect ratios < 10:1 and >100:1 for aspect ratios >10:1); minimum mask undercut (<50 nm per edge for a 40-micron deep etched feature); minimum notching (<10 nm notching per edge at the Si/SiO_2 interface across a 150-mm SOI wafer); and minimum Bosch process etched feature sidewall scalloping (<25 nm).

PATTERNING

SolarSemi MC204 Microcluster Spin Coating System. An automated system that allows the precision application of photoresist to wafers and pieces up to 200-mm (8-inch) diameter. This system expands the preloaded available resist families available for use on the four steppers in MDL, and provides Edge Bead Removal capabilities for both full wafers and odd-shaped pieces.

Solitec 5110C manual photoresist spinner. This acquisition replaces an existing manual spinner capability in MDL.

Semitool 870S Dual Spin Rinser Dryer. This system provides an enhanced non-manual capability to clean the surfaces of 100-mm (4-inch) diameter and 150-mm (6-inch) diameter wafers prior to the application of photoresist to them.

Suss MA6 mask aligner MO Exposure Optics upgrade. The installation of two Köhler integrators based on fused silica microlens arrays into the existing DUV Suss MA6 mask aligner allows homogeneity of both the light intensity and the angular spectrum of the mask illumination light. This decouples the exposure light from the lamp source and provides telecentric illumination providing improved critical dimension (CD) uniformity and overlay accuracy. Illumination uniformity was improved from ±4% to ±2% over the full mask field. Improved uniformity was desired to improve the yield on the larger arrays being processed for the IR FPA task deliverables.

CHARACTERIZATION

Veeco Wyko NT9300 Optical Profiler upgrade. 50X optics were added to improve the precision by more than a factor of two on this noncontact optical profiler that uses two technologies to measure a wide range of surface heights. The phase-shifting interferometry (PSI) mode allows one to measure smooth surfaces and small steps, while the vertical scanning interferometry (VSI) mode allows one to measure rough surfaces and steps up to several millimeters high.

Frontier Semiconductor FSM 128-NT (200 mm) Manual Film Stress and Wafer Bow Mapping System. This

JPL's Fire Department held a multi-agency emergency response training exercise centered around MDL in 2013. It involved a local hospital and multiple fire departments to improve resource allocation in the event of an emergency.

acquisition added to and modernized this characterization capability in MDL.

Obsolete and little used capabilities were also retired to provide additional lab space in MDL's cleanrooms. Specifically, a Solitec 5110-ND manual photoresist spinner was replaced, and a dated 100-mm (4-inch) wafer diameter four-tube Tystar LPCVD system was removed. Only back-up capability was lost with the removal of three of the growth tubes, but the rarely used ability to deposit doped polysilicon eliminated with the fourth tube will no longer be available in MDL.

In addition to regular facilities maintenance, a number of other infrastructure renewals were implemented in 2013 to accommodate expanded operations, achieve regulatory compliance, and improve safety monitoring:

- Annex cryo dewar staging area with improved drainage was added.
- Additional safety monitoring sensors were installed and the Notifier Life Safety System Software was rewritten, installed, and tested.
- One Emergency Safety Shower was added and one was replaced.
- CO_2 Wet Bench Fire Suppression Cylinders were hydro tested.
- An improved monitoring system was installed for the cleanroom Recirculating Units (RCUs) for energy management.
- The main building power switchbank for Emergency Back-Up was serviced.
- An updated JACE environmental control system interface was installed.

Numerous MDL outreach and marketing activities occurred in 2013. More than 90 MDL tours were given. An emergency response training exercise centered around MDL in 2013. It involved multiple fire departments, a local hospital, the JPL Fire Department and other JPL organizational elements to improve the efficiency of resource allocation in the event of an emergency in the MDL facility which utilizes Acutely Hazardous Materials (AHMs) in its operations.

Below: An MDL scientist loads a wafer for analysis into MDL's new Frontier Semiconductor FSM 128-NT Film Stress and Wafer Bow Mapping System.

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
- Tystar (150mm /6-inch) Low-Pressure Chemical Vapor Deposition (LPCVD) with 2 Tubes for:
  - Low Stress Silicon Nitride
  - Atmospheric Wet/Dry Oxidation
- Carbon Nanotube Furnace Systems (2)
- Electroplating Capabilities
- Molecular Beam Epitaxy (MBE)
  - Veeco GEN200 (8-inch) Si MBE for UV CCD Delta Doping (Silicon)
  - Veeco Epi GEN III MBE (Antimonide Materials)
  - Riber MBE for UV CCD Delta-Doping (Silicon)
  - Riber Device MBE (GaAs)
- Thomas Swann Metallo-Organic Chemical Vapor Deposition (MOCVD) System

Lithographic Patterning

- Electron-Beam (E-beam) Lithography: JEOL JBX9300FS E-beam lithography system with a 4-nm spot size, 100,000-volt acceleration voltage, ability to handle wafers up to 9 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 7 mm of sag
- GCA Mann Wafer Stepper with custom stage allowing different sizes and thicknesses of wafers (0.7-µm 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) with MO Exposure Optics upgrade
  - Suss BA-6 (UV400) with jigging supporting Suss bonder
- Wafer Track/Resist/Developer Dispense Systems:
  - Suss Gamma 4 Module Cluster System
  - Site Services Spin Developer System
  - SolarSemi MC204 Microcluster Spin Coating System
- Yield Engineering System (YES) Reversal Oven
- Ovens, Hotplates, and Manual Spinners (including a newly refurbished Solitec 5110C spinner)

Dry Etching

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

Fluorine-Based Plasma Etching Systems

- STS Deep Trench Reactive Ion Etcher (DRIE) with SOI Upgrade
- Plasmatherm Versaline VLN-LL-DSE Deep Silicon Etcher (DSE/DRIE)
- 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 including new Semitool 870S Dual Spin Rinser Dryer
- Chemical Hoods (7)
- Acid Wet Processing Benches (8)
- Tousimis 915B Critical Point Dryer
- Rapid Thermal Processors/Contact Alloyers (2)
- Polishing and Planarization Stations (5)
- Strasbaugh 6EC Chemical Mechanical Polisher
- Precitech Nanonform 250 Ultra Diamond Point Turning System
- SET North America Ontos 7 Native Oxide (Indium Oxide) Removal Tool
- SurfX 400L Atmospheric Surface Preparation System
- New Wave Research EzLaze 3 Laser Cutting System
- Indonus HF VPE-150 Hydrofluoric Acid Vapor Phase Etcher

Above: View of the rear of MDL's new Plasmatherm Versaline Deep Silicon Etcher (DSE/DRIE) showing the etch chamber, gas pod, and a secondary monitor for service maintenance residing outside of the cleanroom proper.

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) (Dektak 8 & Alphastep 500)
- Frontier Semiconductor FSM 128 Film Stress Measuring system
- Frontier Semiconductor FSM 128-NT (200mm/8-inch) Film Stress and Wafer Bow Mapping 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 EDX
- Nikon and Zeiss Inspection Microscopes with Image Capture (3)
- Olympus LEXT 3D Confocal Microscope
- Electrical Probe Stations with Parameter Analyzers (2)
- RPM2035 Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectroscopy
- PANalytical X'Pert Pro MRD with DHS High Temperature Stage X-ray Diffraction System
- Surface Science SSX501 XPS with Thermal Stage
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)
- Nanometrics ECV Pro Profiler
- VEECO / WYKO NT 9300 Surface Profiler (including 50X optics)

Journal Publications

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Conference Proceedings and Publications

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2. G. Chattopadhyay, "Technologies for Terahertz Science," *IEEE MTT-S International Microwave Symposium Digest,* Seattle, Washington, June 2013.

3. T. Reck, G. Chattopadhyay, and W. R. Deal, "A Tandem Coupler for Terahertz Integrated Circuits," *IEEE MTT-S International Microwave Symposium Digest,* Seattle, Washington, June 2013.

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39. A. D. Jewell, J. Hennessy, F. Greer, E. Hamden, M. Hoenk, and S. Nikzad, "Enabling High Performance Instruments for Astronomy and Space Exploration with ALD," *57th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication,* Nashville, Tennessee, May 2013 (invited paper).

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New Technology Reports

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2. J. Siles, K. Cooper, T. Reck, C. Lee, E. Schlecht, C. Jung, R. Lin, A. Peralta, G. Chattopadhyay, I. Mehdi, and S. Sin, “Ultra-Compact Multi-Pixel Heterodyne Submillimeter-Wave Transceiver Using Vertically-Stacked Thin-Metal Plates for MMIC Circuit Packaging with 3D Level of Integration,” NTR: 49151 (May 2013).

3. C. Jung, T. Reck, G. Chattopadhyay, J. Siles, R. Lin, I. Mehdi, C. Lee, K. Cooper, and A. Peralta, “Multi-Step DRIE Process to Fabricate Silicon-Based THz Components,” NTR: 49123 (April 2013).

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Patents

1. G. Chattopadhyay, E. Schlecht, C. Lee, R. Lin, J. Gill, S. Sin, and I. Mehdi, “670 GHz Schottky Diode Based Subharmonic Mixer with CPW Circuits and 70 GHz IF,” US 20120280742A1.

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3. D. Z. Ting, S.V. Bandara, C. J. Hill, and S. D. Gunapala, “Complementary Barrier Infrared Fetector (CBIRD),” U. S. Patent No. 8,368,051 B2. Issued 2/5/13.

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Book Contributions

1. G. Chattopadhyay, N. Llombart, A. Neto, and A. Freni, “Reflector Antennas for Terahertz Imaging,” *Handbook of Modern Reflector Antennas and Feed Systems for Space and Ground Applications*, edited by S. Rao, L. Shafai, and S. Sharm (Artech House, 2013), Vol. 3, Chap. 4, p. 145.

2. D. Z. Ting, A. Soibel, S. A. Keo, C. J. Hill, J. M. Mumolo, L. Höglund, J. Nguyen, A. Khoshakhlagh, Sir B. Rafol, J. K. Liu, and S. D. Gunapala, “Mid- and Long-Wavelength Barrier Infrared Detectors,” *The Wonder of Nanotechnology: Quantum Optoelectronic Devices and Applications,* edited by M. Razeghi. L. Esaki, and K. von Klitzing (SPIE Press, Bellingham, WA, 2013), Chap. 17, pp. 379–405.

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Awards and Distinguished Recognition

1. Jonas Zmuidzinas was awarded NASA’s Exceptional Technology Achievement Medal for his work on the development of superconducting astronomical sensors based on SIS and MKID technologies.

2. Chris R. Webster was awarded NASA’s Exceptional Technology Achievement Medal for his work on the development of the tunable laser spectrometer within the Sample Analysis at Mars Investigation on the MSL Mission.

3. G. Chattopadhyay has been selected by the IEEE Microwave Theory and Techniques Society as a Distinguished Lecturer for 2014–2016.

4. Dr. Rakesh Murthy was elected as a member of the IEEE Technical Committee on Micro-Nano Robotics & Automation.

5. Dr. Carl Borgentun was recognized for his work on “High-Power Semiconductor Lasers for in situ Sensing of Atmospheric Gases.” It garnered a best poster award for cutting-edge research on JPL Postdoc research day, July 9, 2013.

6. The IEEE Board of Directors, at its November 2013 meeting, elevated Sarath Gunapala to IEEE Fellow for his contributions to infrared detectors and focal plane arrays.

7. The IEEE Photonics Society awarded Sarath Gunapala the IEEE Photonics Society 2013 Aron Kressel Award for “Pioneering Contributions to the Development of Quantum Structures Based Infrared Detectors and Imaging Focal Plane Arrays.”

8. The SPIE promoted Dr. David Ting’s membership to SPIE Fellow in recognition of his significant service to the society and the greater science community, as well as noteworthy technical achievements.

11. Shouleh Nikzad of MDL was inducted as a fellow of the American Physical Society (APS) for her work on band structure engineering.

12. Shouleh Nikzad was awarded the Pioneer in Medicine Award by the Society for Brain Mapping and Therapeutics for her leadership toward developing ultraviolet imaging technology for non-invasive tumor delineation and bringing the technology to clinical trials.

13. Shouleh Nikzad was invited as a presenter and panelist at the U. S. Congress by the Congressional Caucus on Brain Mapping.

14. Michael Hoenk was selected as best paper (poster) presentation at the Scientific Detector Workshop held in October 2013.

In Memory of Dr. Jeffrey Stern 1961 – 2013

During his tenure at JPL, Dr. Jeffrey Stern continually demonstrated his commitment to the highest levels of technical excellence. As a Senior Member of the Technical Staff, he made significant contributions to the Microdevices Laboratory, in particular in the development of superconducting sensors. His incisive work helped to enable cutting-edge sensors for advanced NASA missions as well as ground-based observatories. Dr. Stern's work had international resonance, too. He fabricated and space-qualified superconductor–insulator–superconductor mixer chips for the Heterodyne Instrument for the Far-Infrared (HIFI) on the European Space Agency's Herschel Space Observatory. Herschel's measurements, supported by Jeff's innovations, have led to a deeper understanding of the interstellar medium. Ever inventive, Dr. Stern pioneered the use of phonon-cooled niobium nitride mixers, the fabrication of terahertz waveguide components using lithographic techniques, and the development of new detectors for optical communications. Jeff was the first person in the U. S. to make a functional superconducting nanowire single-photon detector (SNSPD) (2004), fabricate a functional SNSPD in NbTiN (2006), and fabricate 4- to 16-pixel arrays (2005–2007). In 2012–2013, Dr. Stern designed and fabricated fiber-optic-coupled SNSPDs from tungsten silicide with the highest efficiency demonstrated to date for 12-pixel arrays for an optical communications link with NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) orbiting the Moon. His final accomplishment was the invention of a 64-pixel free-space-coupled SNSPD having an active area over 100 times greater than other state-of-the-art devices. Designed to be mounted on a large telescope such as the 5-meter Hale Telescope at Caltech's Palomar Observatory in California, it can be used for optical communication with interplanetary spacecraft, observing ultrafast astrophysical events, and experimentally measuring quantum mechanical effects over large distances.

Dr. Stern's innovations and leadership helped create a world-leading team at JPL's Microdevices Laboratory. We will remember him not only as an exceptional and dedicated scientist, but also as a dear colleague and friend.

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

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