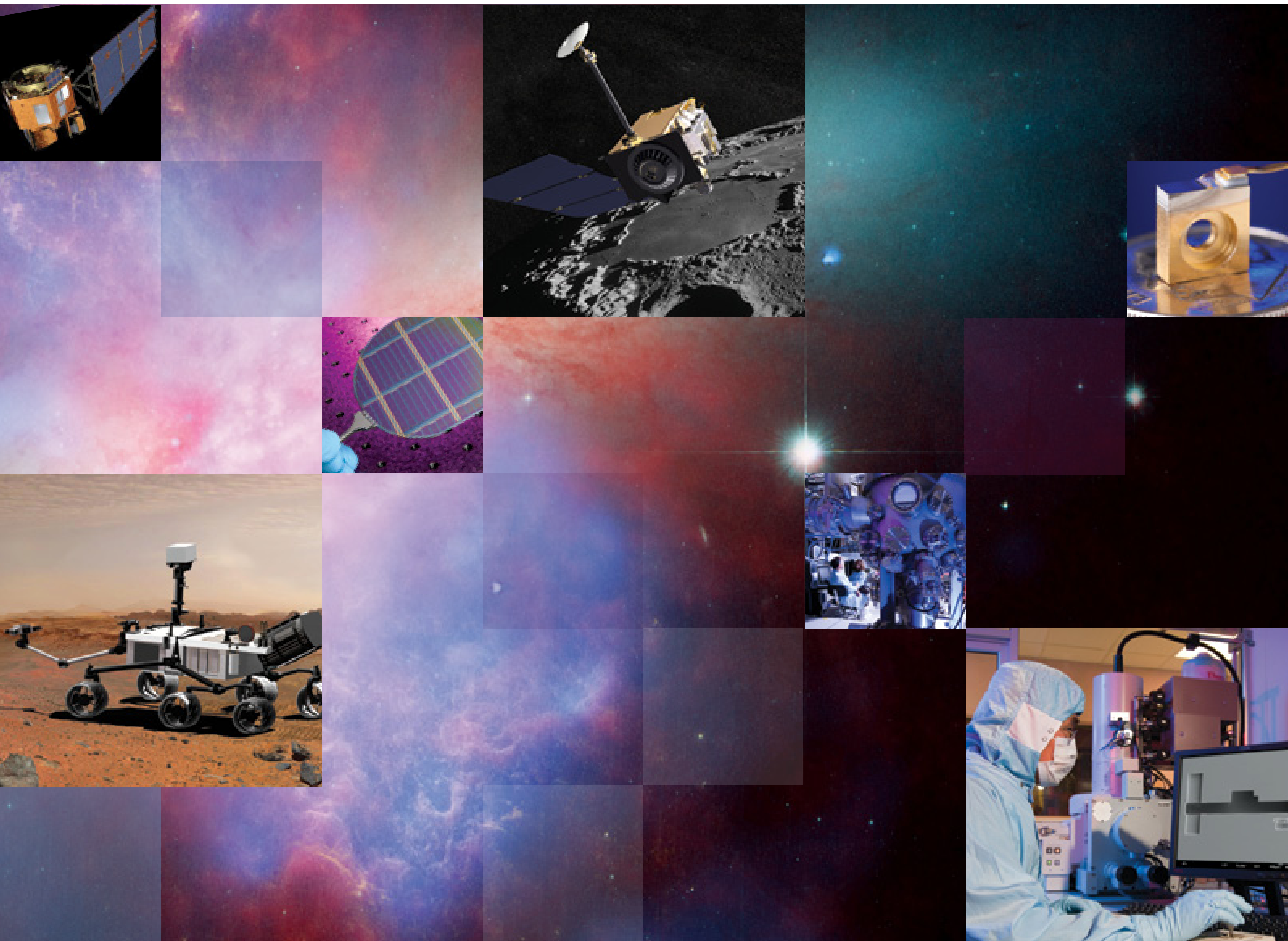
National Aeronautics and Space Administration

Jet Propulsion Laboratory

Microdevices Laboratory

2010 ANNUAL REPORT



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

The work and contributions of the talented MDL scientists, technologists, and research staff hold the promise of further extensions of our ability to peer into the far reaches of our solar system, other galaxies, and the very beginnings of our universe. At Microdevices Laboratory, we believe **Big Things Come From Small Technologies**.

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Did You Know?

MDL technologies are key to the following instruments:

Herschel SPIRE (Spectral and Photometric Imaging Receiver)

The Herschel Space Observatory (pictured on page 20) is the largest infrared space observatory launched to date. Herschel observes at wavelengths that have never previously been explored. SPIRE, one of the three Herschel instruments, employs arrays of spider-web bolometers with NTD-germanium temperature sensors as its detectors. Spider-web bolometers designed and fabricated at MDL are currently the most sensitive detectors available.

Herschel HIFI (Heterodyne Instrument for the Far-Infrared)

The Heterodyne Instrument for the Far-Infrared (HIFI) is a very high resolution heterodyne spectrometer. The local oscillators (LO) are an essential part of heterodyne receivers. The MDL developments in LO capability have enabled several spaceflight instruments (MLS, MIRO, Herschel HIFI) and are critical components in new heterodyne spectrometers for planetary science applications.

Moon Mineralogy Mapper

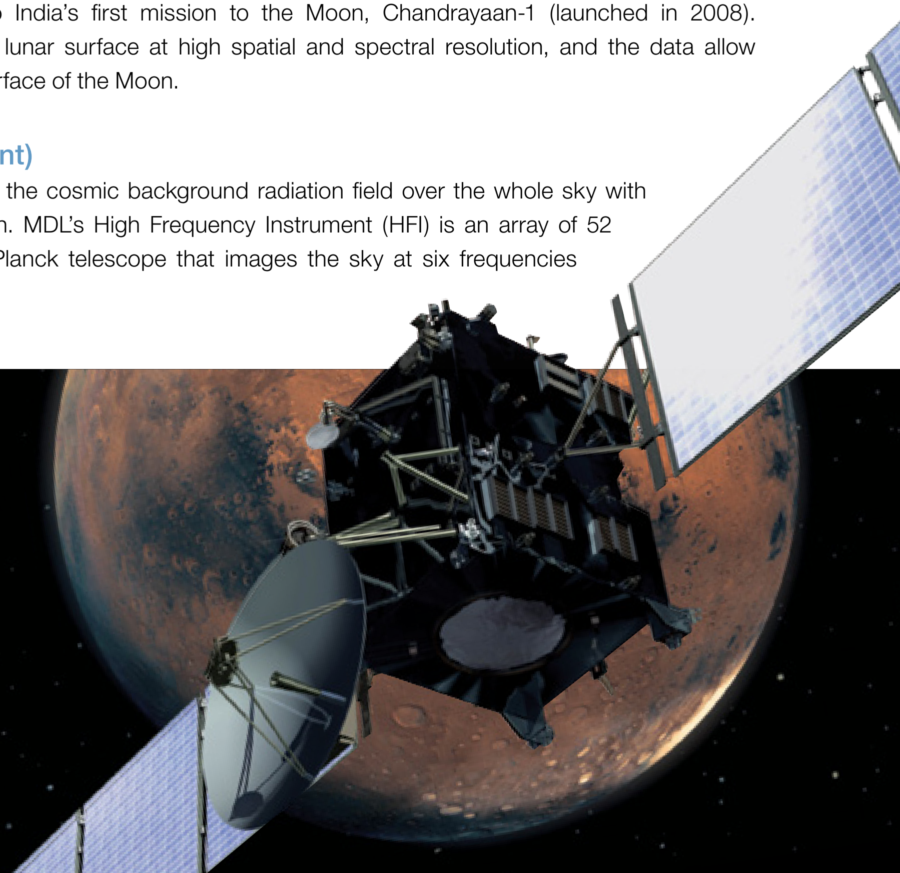
A curved grating fabricated at MDL is the key dispersive element in the Moon Mineralogy Mapper (M3), a state-of-the-art imaging spectrometer contributed by NASA to India's first mission to the Moon, Chandrayaan-1 (launched in 2008). M3 provided the first mineralogical map of the lunar surface at high spatial and spectral resolution, and the data allow scientists to determine the composition of the surface of the Moon.

Planck HFI (High Frequency Instrument)

Planck is designed to image the anisotropies of the cosmic background radiation field over the whole sky with unprecedented sensitivity and angular resolution. MDL's High Frequency Instrument (HFI) is an array of 52 bolometric detectors in the focal plane of the Planck telescope that images the sky at six frequencies between 100 GHz and 857 GHz.

MIRO (Microwave Instrument on the Rosetta Orbiter)

MIRO's 557-GHz radiometer utilizes subharmonic planar diode mixers and multipliers fabricated in MDL to study gases given off by comets. The European Space Agency's Rosetta Orbiter was launched in March 2004, on a 10-year journey to rendezvous with Comet 67 P/Churyumov-Gerasimenko.



EOS MLS (Earth Observing System Microwave Limb Sounder)

High-frequency 150-240-640 GHz radiometers with subharmonic planar diode mixers and a 2.5-THz radiometer with a fundamental planar Schottky diode mixer were fabricated at MDL and flown on the Aura spacecraft (launched on July 15, 2004) to improve the understanding of ozone chemistry in the Earth's stratosphere, especially how ozone is depleted by processes of chlorine chemistry.

Hyperion

The first MDL electron-beam-fabricated grating to fly in space was utilized in the Hyperion imaging spectrometer aboard the NASA EO-1 spacecraft. The Hyperion instrument was built by TRW, Inc. (now Northrop Grumman Space Technology), was launched in November 2000, and is still in operation today for the United States Geological Survey.

TLS (Tunable Laser Spectrometer)

Scheduled to launch in the fall of 2011, TLS aboard the Mars Science Laboratory will assess whether Mars ever was, or is still today, an environment able to support microbial life. Enabled by the MDL interband cascade laser, TLS is capable of determining atmospheric methane abundance to a limit of 1 part per trillion with SAM preconcentration.

DLRE (Diviner Lunar Radiometer Experiment) and MCS (Mars Climate Sounder)

The Diviner Lunar Radiometer is one of seven instruments aboard NASA's Lunar Reconnaissance Orbiter spacecraft, which was launched on June 18, 2009. Diviner is a nine-channel infrared filter radiometer based on the design of the Mars Reconnaissance Orbiter Mars Climate Sounder (MCS).

CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)

Two curved gratings fabricated at MDL serve as the dispersive elements for CRISM, an imaging spectrometer that has been flying aboard the Mars Reconnaissance Orbiter since 2005. CRISM seeks to find traces of past and present water on the Martian surface and to map the geology, composition, and layering of surface features.

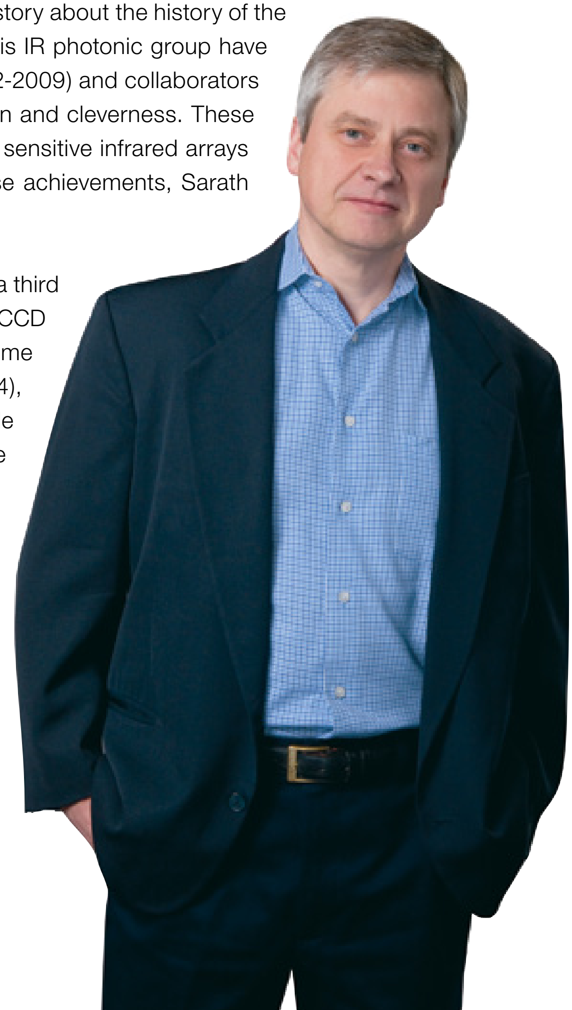
ARTEMIS (Advanced Responsive Tactically Effective Military Imaging Spectrometer)

JPL teamed with Raytheon to create ARTEMIS (pictured on page 7), a high-performance imaging spectrometer that utilizes an MDL-designed and e-beam-fabricated curved grating and an MDL micromachined slit. ARTEMIS is flying aboard the TacSat-3 U.S. military reconnaissance satellite to provide information about normally undetectable activities, objects, and substances, within 10 minutes of tasking. The Air Force Space Command assumed control of the sensor in May 2010.

Letter from the Director

Technology development requires vision, courage, and conviction. Vision helps us discern the possibilities emerging from the fog of the distant future. Once the vision becomes clear, we need courage to embark on the long road that leads us to our goal, and conviction to keep going when things get difficult.

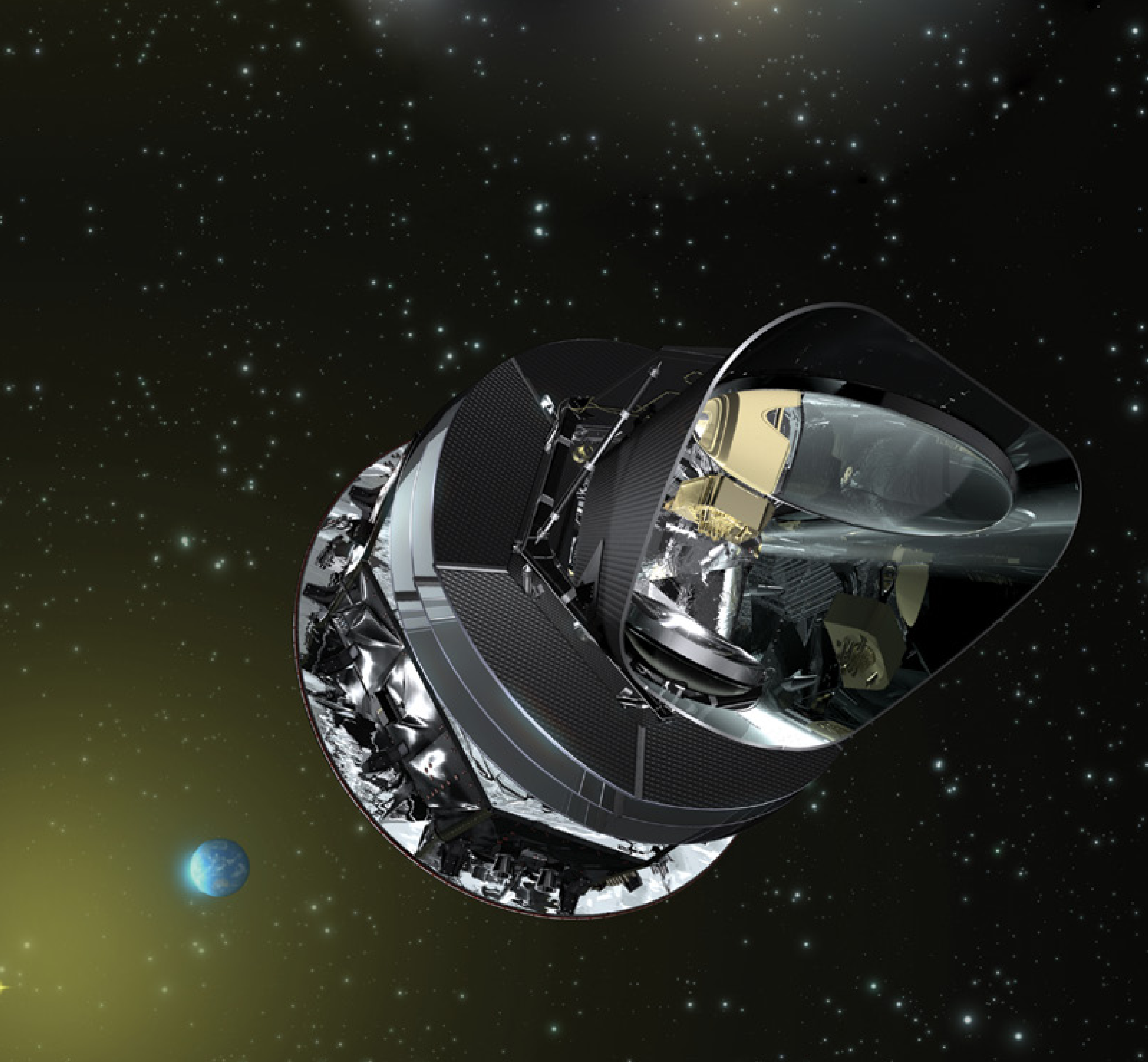
I am reminded of this as I reflect on several awards received by MDL scientists over the past year. Goutam Chattopadhyay was recently named IEEE Fellow in honor of his achievements in Terahertz technology, as exemplified by the SWAT group's contributions to ESA's Herschel Space Observatory. This took plenty of courage and conviction — shortly after I joined the Caltech faculty in 1990, as I listened to presentations on the topic, it was far from clear to me that the effort would ultimately prove successful. The story actually starts in the 1970s, when Caltech's Bob Leighton (1919-1997), JPL's Sam Gulkis, and others, had the vision to suggest a large submillimeter-wave telescope in space. This led to another remarkable act of courage — a Decadal Survey recommendation in 1982 — that prompted NASA to start investing in the technology that led to Herschel. In a recent KNI-MDL seminar, JPL's David Ting told a similar story about the history of the bandgap-engineered III-V infrared detectors that Sarath Gunapala and his IR photonic group have developed. Throughout the 1970s and 1980s, Caltech's Tom McGill (1942-2009) and collaborators envisioned a number of detector structures with increasing sophistication and cleverness. These ideas served as the starting point for the MDL group's demonstration of sensitive infrared arrays capable of relatively high operating temperatures. In recognition of these achievements, Sarath Gunapala was selected for the IEEE Distinguished Lecturer Award.



Erik Fossum's induction into the National Inventors Hall of Fame provides a third example. As a Distinguished Visiting Scientist, Fossum was exposed to the CCD imager work that James Janesick had started at JPL in the 1970s. By the time Fossum joined JPL, and with help from Caltech's Jim Westphal (1930-2004), the JPL CCD effort had fulfilled its vision of providing a camera for the Hubble Space Telescope. In the early 1990s, Fossum had the vision and courage to propose a different type of imager — the CMOS active pixel sensor. Today, low-cost CMOS imagers are ubiquitous in cell phone cameras, and high-end versions are approaching CCD performance.

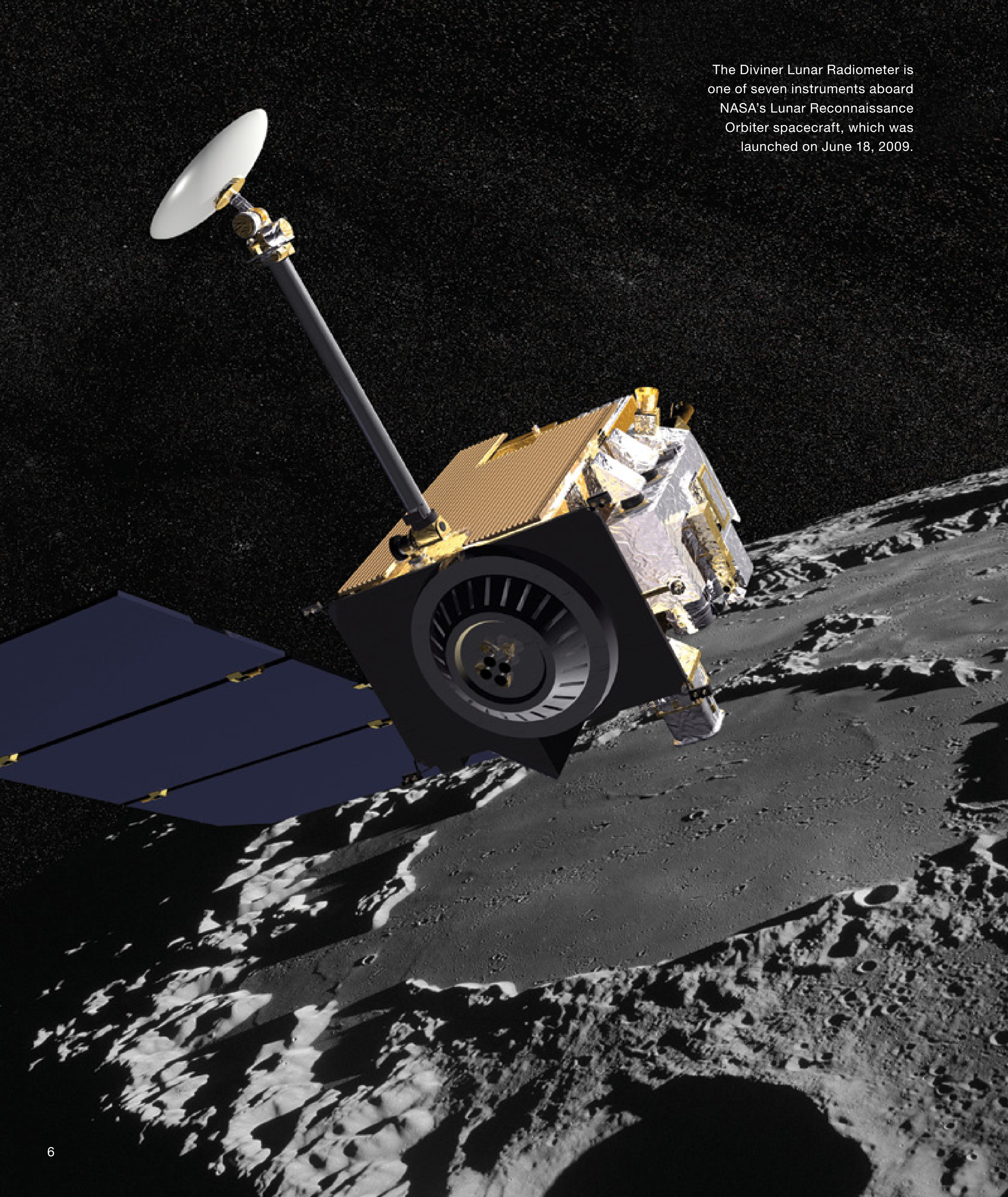
Our nation is once again considering its future in science and technology. Let's move forward with the same vision, courage, and conviction shown by our predecessors.

Jonas Zmuidzinas
Director, JPL Microdevices Laboratory



On May 14 2009, Herschel and Planck were launched. Now, both spacecraft are busy supplying data to scientists on Earth. These European Space Agency (ESA) missions have significant NASA participation: four out of the five science instruments on Herschel and Planck rely on NASA-developed technologies. Many of these technologies — in particular the photon detectors at the heart of several of the science instruments — were developed and produced at the JPL Microdevices Laboratory (MDL).

Image courtesy ESA.



The Diviner Lunar Radiometer is one of seven instruments aboard NASA's Lunar Reconnaissance Orbiter spacecraft, which was launched on June 18, 2009.

Letter from the Division Manager

We have now entered our third decade of operation of the Microdevices Laboratory at JPL and believe it to be as vital today as it was when we first embarked on this venture. The MDL continues to have diversity in its technical capability that makes this facility unlike most microdevice facilities in the US. We have had many accomplishments over the last year in both fundamental device research and in engineering delivery to JPL instruments. Many of these accomplishments are detailed in this report.

Our investments have been guided under the leadership of Professor Jonas Zmuidzinas, who has continued as Director of the MDL. A key investment this year was the purchase and installation of a flip-chip bonder. Although this piece of equipment will have broad application to detector development at JPL, it will first be used to hybridize infrared detectors that we've been developing over the past few years. We have also continued the commissioning of our new eight-inch silicon MBE machine in MDL, the goal of which is to demonstrate large format, delta-doped CCDs consistent with science requirements in astronomy and physics.

As you will read in this Annual Report, it has been a busy and productive year for the MDL. As we enter our third decade of operation we look forward with high expectation to continued innovation and invention in our microdevice and nano technologies that will enable JPL to make unprecedented discoveries in pursuit of its prime mission, contributing in unique ways to projects of national interest and enabling tomorrow what we can only imagine today.

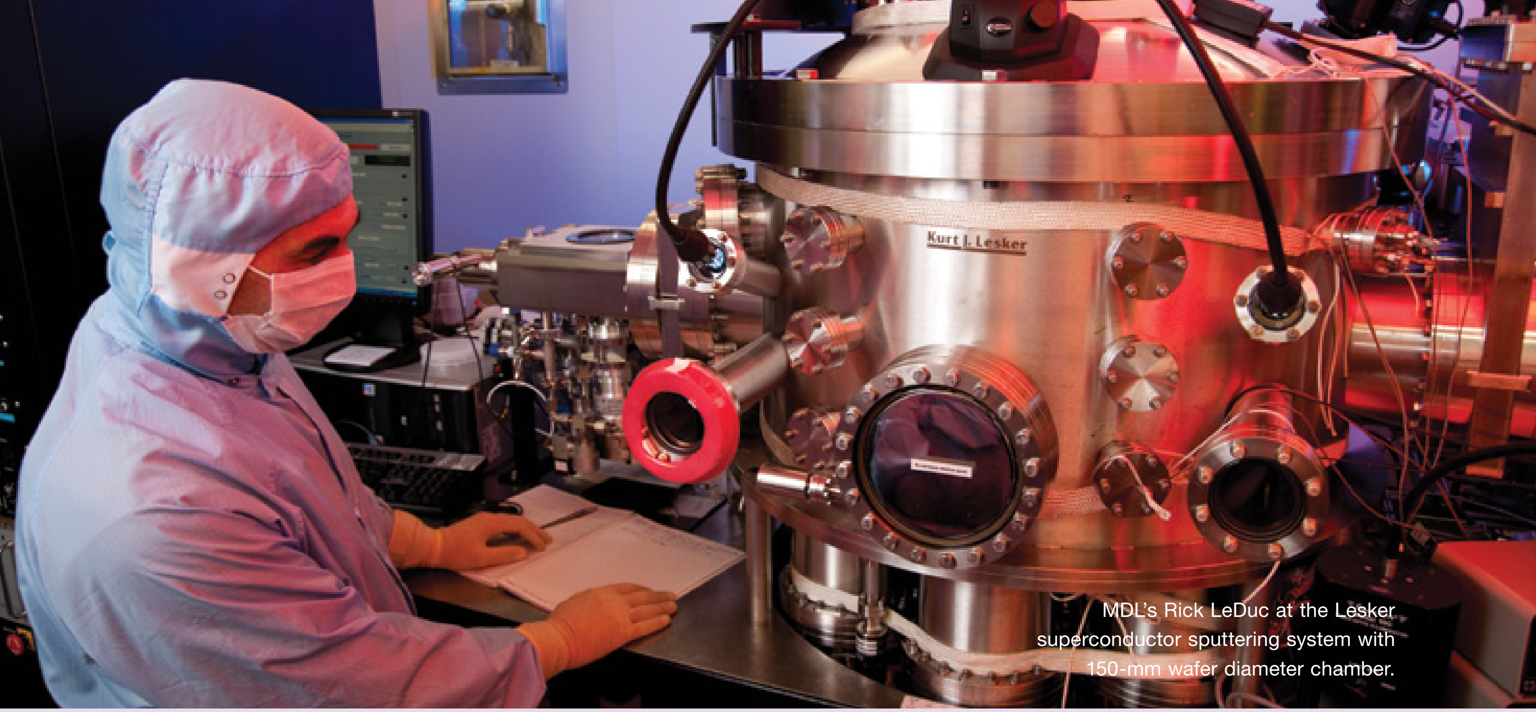
Thomas S. Luchik
Manager, Instruments & Science Data Systems Division

Infrastructure

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.

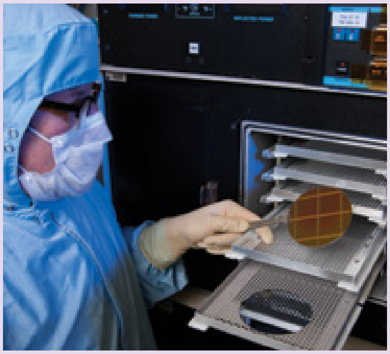
In MDL's continuing saga of growth and renewal, a number of significant investments and infrastructure improvements were made in 2010.

MDL's John Liu and Jason Mumolo at the SET FC-300 flip-chip bonder.



MDL's Rick LeDuc at the Lesker superconductor sputtering system with 150-mm wafer diameter chamber.

RO / DI Water Pre-Filtration Plant



Branson Plasma Asher

INFRASTRUCTURE IMPROVEMENTS:

1. Digital humidity and process cooling water temperature monitors added with auto alarm state notification (April).
2. Bldg. 302 external facing seams renewed and sealed (May).
3. Spare blower purchased and received for the main air intake to MDL, AH1 {long-lead item single-point failure}(June).
4. RO/DI water pre-filtration plant replacement / upgrade (June).
5. MDL compressed dry air system replacement / upgrade (with 2 new air compressors, new AC manifold, new dryer, and new AC receiver tank) (September).

EQUIPMENT INVESTMENTS/UPGRADES:

1. SET FC-300 flip-chip bump bonder enabling precision alignment and indium bump bonding of large focal plane arrays (FPAs).
2. AJA load locked thermal co-evaporator for deposition of alloys of bismuth-antimony-tellurium thin films for broadband IR bolometers.
3. AJA load locked UHV e-beam evaporator replacing a non-load locked e-beam evaporator (Sloan 1) for central processing contact applications.
4. Refurbished Branson plasma asher to augment existing capabilities, eliminating single-point failure in process stream of numerous tasks.
5. Lesker superconductor sputtering system 150-mm wafer diameter chamber upgrade.

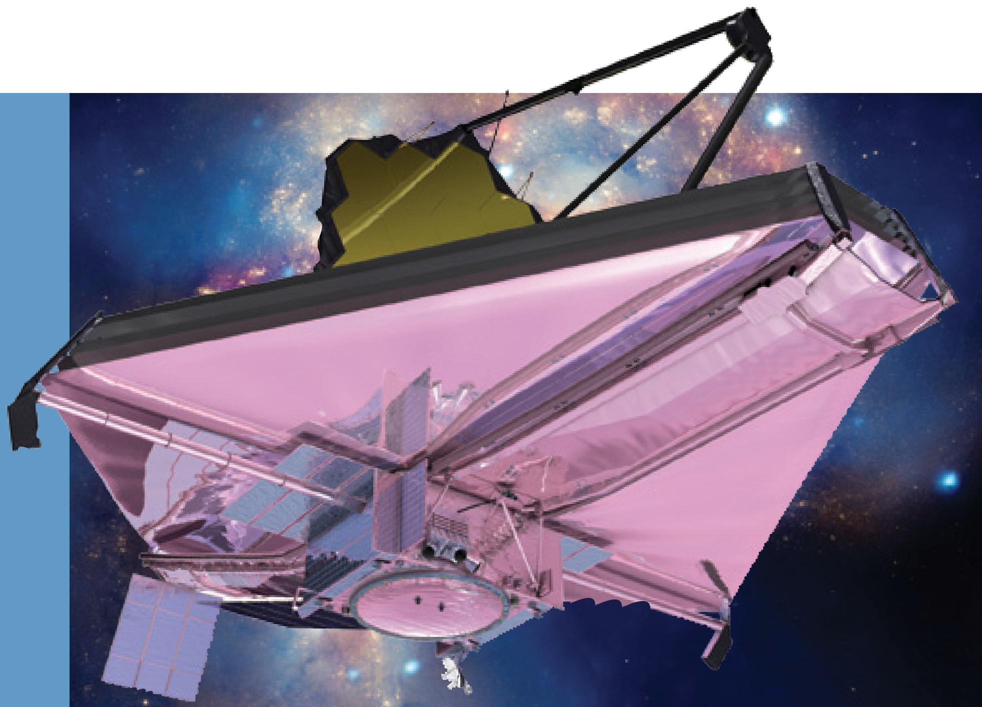
Two other significant activities worthy of note for this report were 1) The completion of a successful in-depth NASA review of the MDL facility and operations by the NASA Operations Engineering Panel (OEP) November 17–20, 2009; and 2) Significant participation in outreach activities with 13,260 members of the public physically accessing the facility at the JPL Open House (May 15–16, 2010) with an average of 5 tours per month given during the year.

Optical Components

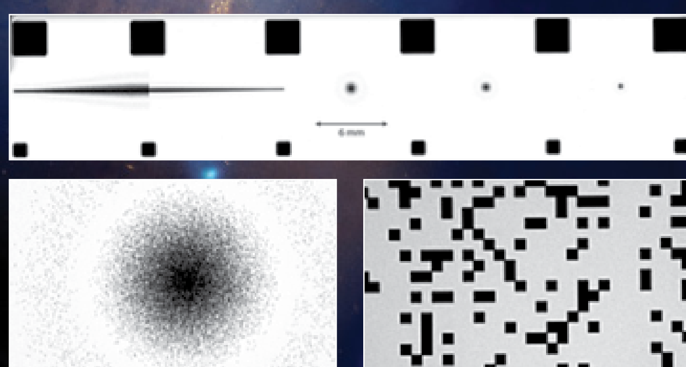
MDL's Optical Components Group utilizes state-of-the-art electron-beam lithography techniques to fabricate unique optics that enable JPL instruments to achieve unmatched performance. In addition to binary nano-lithography, we have developed techniques for fabricating precision analog surface relief (gray-scale) profiles in polymer resists and substrate materials. This allows creation of nearly arbitrary transmissive and reflective diffractive optics such as blazed gratings, Fresnel lenses, and computer-generated holograms, for wavelengths ranging from ultraviolet to long-wave infrared. Further, we have developed the capability to electron-beam fabricate these diffractive optics on non-flat (convex or concave) substrates with several millimeters of height variation. MDL has fabricated many convex and concave gratings for NASA and non-NASA flight instruments, including the recent Moon Mineralogy Mapper, which provided evidence of water on the surface of the Moon.

MDL Flight Occulters Enable Detection and Characterization of Orbiting Exoplanets

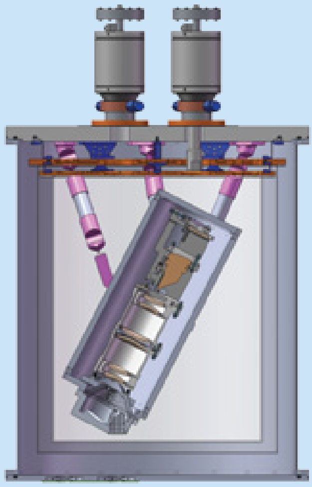
MDL completed fabrication of five flight occulting masks for the James Webb Space Telescope (JWST) Near Infrared Camera (NIRCam) coronagraph. The occulters are binary half-tone patterns composed of near-wavelength-size holes and islands of thick aluminum, patterned by electron-beam lithography followed by plasma etching. The half-tone patterns realize carefully designed Airy function apodizing masks that block the 2- to 5-μm wavelength star-light focused onto the occulter. The remaining light that passes through the NIRCam coronagraph is reimaged to enable detection and characterization of orbiting exoplanets.



Above: Artist concept of the James Webb Space Telescope (JWST).



Right: Occulting mask for the JWST Near Infrared Camera (NIRCam) including high-magnification images that show the half-tone nature of the occulting spots.



Collaboration to Develop Premier Airborne Earth Observing Thermal Imaging Spectrometer

The MDL's Optical Components and Infrared Photonics Technology Groups are collaborating with the Earth Surface Science Group (JPL Division 32) to develop the Hyperspectral Thermal Emission Spectrometer (HyTES). HyTES will be the premier airborne Earth-observing thermal imaging spectrometer for Earth science. The incoming image from the instrument's telescope is perfectly sliced by a slit fabricated in the MDL using micromachining techniques to achieve ultimate precision in straightness and uniformity. The spectrometer is a compact, high-throughput Dyson optical relay that utilizes a MDL electron-beam-fabricated concave diffraction grating that provides high-efficiency dispersion over the instrument's 8 to 12 μm passband. Finally, an MDL-fabricated quantum-well infrared photodetector (QWIP) array provides unsurpassed uniform broadband response of both spatial and spectral information.

Above: Design for JPL's Hyperspectral Thermal Emission Spectrometer (HyTES) showing Dyson imaging spectrometer utilizing MDL-fabricated components: precision micromachined slit, electron-beam-fabricated concave grating, and QWIP.

Significant Progress Made on Gratings Critical to the Study of Potential Hazards to the Earth's Coastal Ecosystems and Communities

During the past year, we have made significant advances in developing low-polarization sensitivity gratings. Such gratings are critical for Earth observing imaging spectrometers that aim to accurately measure ocean color for studying episodic hazards and pollutants on coastal ecosystems and communities. Imaging spectrometry of these regions is difficult due to the low ocean reflectance and unknown atmospheric polarization, hence the need for low-polarization sensitivity optical systems — primarily the grating. Realization of low-polarization gratings is challenging due to the inherent nature of a grating to interact differently with light polarized parallel versus perpendicular to the grooves. However, through precise design of the groove shape and coating, we have demonstrated electron-beam-fabricated gratings that exhibit less than 2% polarization sensitivity over the wavelength range 350 nm to 1000 nm. For JPL's Portable Remote Imaging Spectrometer (PRISM), we fabricated a low-polarization sensitivity grating that is 2.7 inches in diameter with more than 3 mm of center-to-edge height variation (sag).

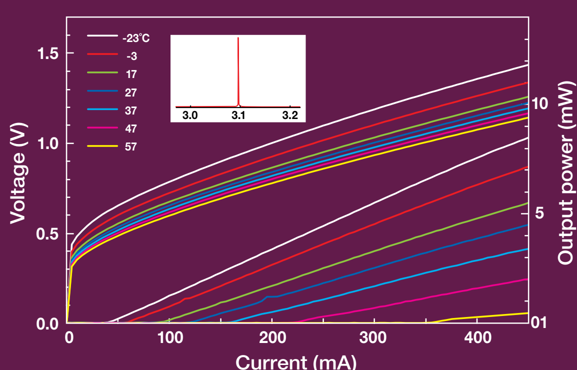
Right: Low-polarization sensitivity concave grating for JPL's Portable Remote Imaging Spectrometer.

Semiconductor Lasers

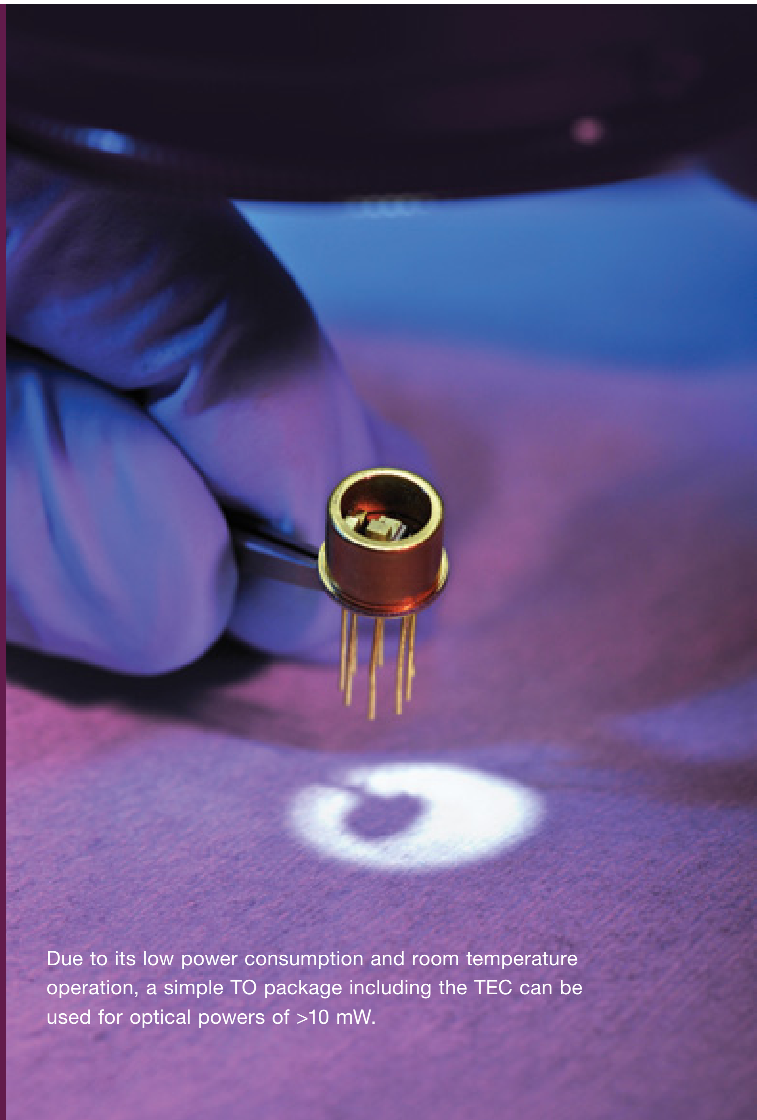
JPL and NASA have a long history of flying tunable diode laser (TDL) spectrometers in Earth and planetary missions for atmospheric and trace gas analysis. Most of the semiconductor lasers of interest require unique characteristics that are often unavailable commercially. For this reason, MDL has been involved in the design and fabrication of space-qualified semiconductor lasers since its inception. Two of the more significant accomplishments that have been made are the delivery of the first InGaAsP 2.06-µm DFB semiconductor laser for detection of water and carbon dioxide isotopes to Mars Volatiles and Climate Surveyor (Mars 98 mission) and the delivery of the first 3.27-µm interband cascade laser for detection of methane and its isotopes. The latter is the heart of the tunable laser spectrometer (TLS) on Mars Science Laboratory (MSL) scheduled for launch in 2011.

Progress Towards Development of Low Power Consumption Lasers for Planetary Atmospheric Studies

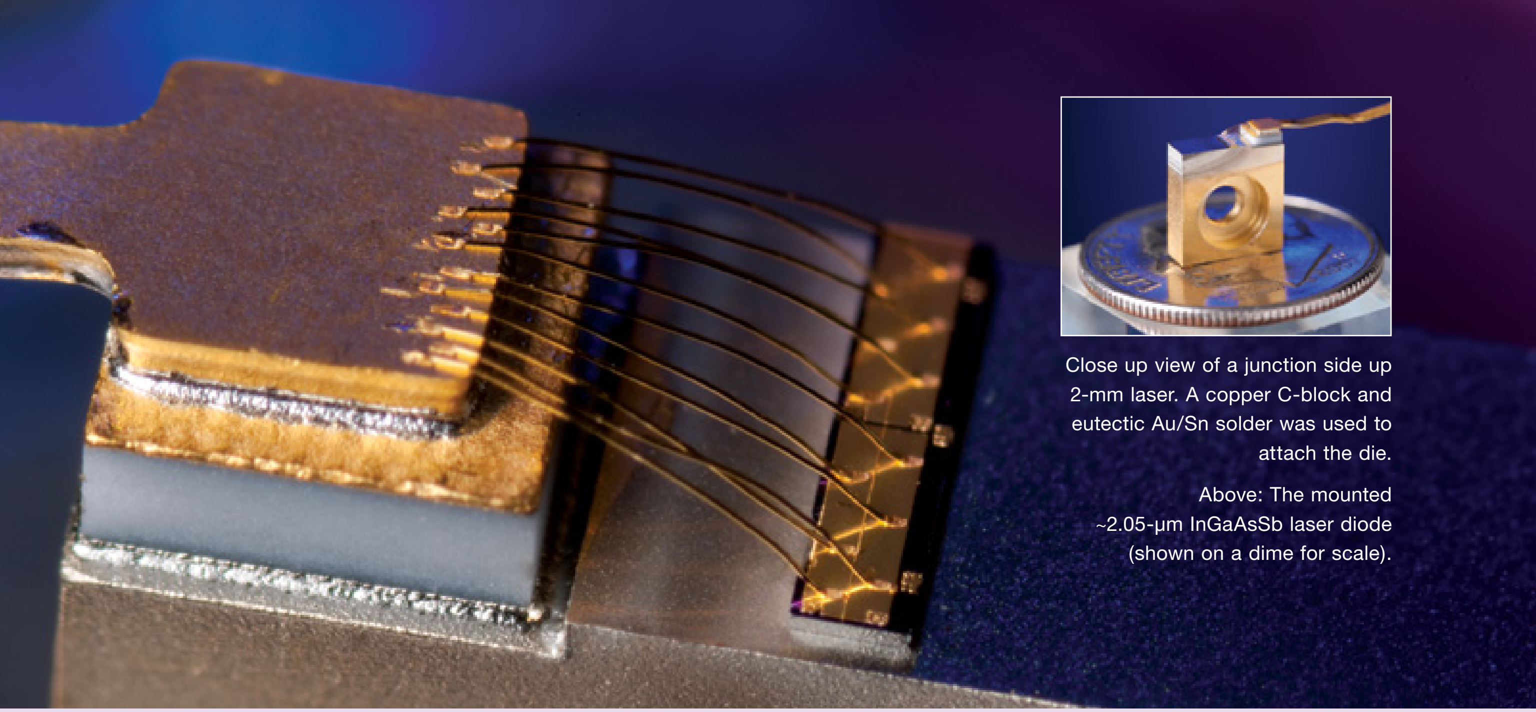
MDL has demonstrated single spatial-mode ridge waveguide semiconductor diode lasers operating continuous wave up to 60C in the 3 µm wavelength range. The fabricated lasers operate in CW mode at room temperature with output powers exceeding 5 mW and have power consumption of less than 0.2 W at the output power of 1 mW (sufficient for many spectroscopic applications).



Above: CW light-current-voltage characteristics of 2.5-mm-long, 5-µm-wide ridge waveguide devices with thick Si_3N_4 coating operating at various temperatures as indicated at the graph. Insert: Laser emission spectrum at 17C.



Due to its low power consumption and room temperature operation, a simple TO package including the TEC can be used for optical powers of >10 mW.

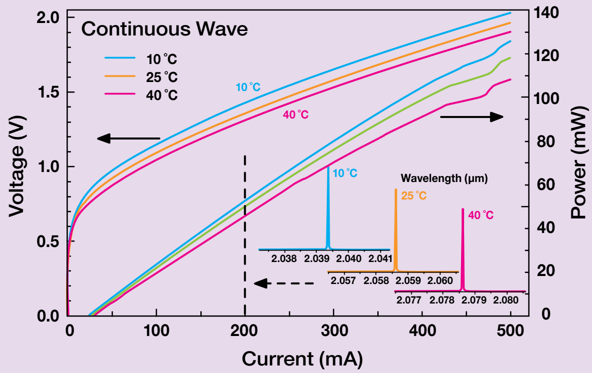


Close up view of a junction side up 2-mm laser. A copper C-block and eutectic Au/Sn solder was used to attach the die.

Above: The mounted ~2.05-μm InGaAsSb laser diode (shown on a dime for scale).

MDL Fabricates Record High-Power, Single-Spatial-Mode Lasers at ~2.05 μm

The NRC Committee on Earth Science and Applications from Space has recommended the proposed Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission to produce global atmospheric column CO_2 measurements using laser remote sensing of CO_2, with the goal of enhancing understanding of the role of this gas in the global carbon cycle. The sensitivity analysis for space-based CO_2 LIDAR measurements has identified transitions in the 1.57- and 2.05-μm absorption bands that are suitable for making global measurements of CO_2. Though both wavelengths could be used for this measurement, JPL has adopted the 2.05 μm absorption line as a long-term preference due to significantly larger CO_2 absorption line strength and significantly less water absorption interference.



Above: CW light-current-voltage (LIV) characteristics of laser at 10, 25, and 40°C. The emission wavelength at 200 mA is shown the inset.

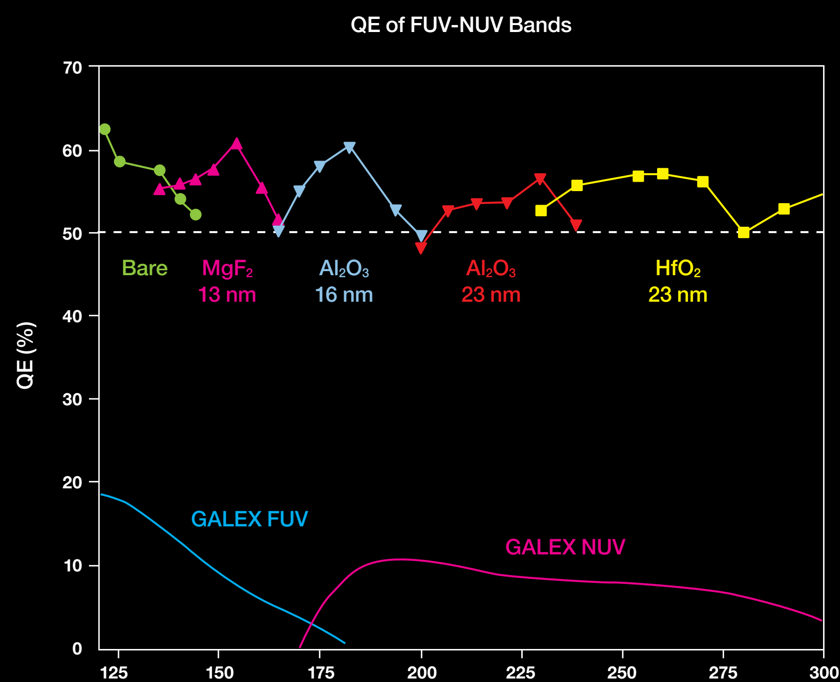
The current laser transmitter used in JPL's Laser Absorption Spectrometer instrument uses optically pumped solid-state lasers for both the seed and the amplifier. Replacement of the seed laser with a monolithic semiconductor laser would greatly improve the instrument stability and long-term reliability. In collaboration with the State University of New York at Stony Brook, we are investigating the viability of GaSb-based laterally coupled distributed feedback lasers as injection seeds.

This year we designed and fabricated record high-power, single-spatial-mode diode lasers operating near 2.05 μm with room-temperature continuous-wave output power exceeding 100 mW. In spite of the low thermal conductivity of the GaSb substrate, the junction-side-up mounted lasers have low thermal resistance of 22 K/W and CW characteristic temperature of 107 K.

Advanced Visible and Ultraviolet Detectors and Imaging Systems

The MDL Advanced UV, Visible, NIR Imagers, Detectors, and Systems Group performs research, development, and flight demonstration, qualification, and delivery of high-performance ultraviolet/visible/near-infrared imagers, cameras, and camera systems. We specialize in advanced epitaxial growth and atomic layer deposition technologies for surface and interface bandstructure engineering, quantum-dot-based devices, nanoscale science, and engineering. We also focus on innovative characterization techniques for novel use of conventional devices. We have had an exciting year with a number of achievements. From setting a world record in achieving highest quantum efficiency (QE) in far-ultraviolet (FUV) and near-UV (NUV) solid-state detector arrays, to advancing UV/visible photon counting detection using solid-state arrays and achieving near zero electron affinity in non-cesiated photocathodes, all of our activities are focused on enabling near- and far-term NASA missions.

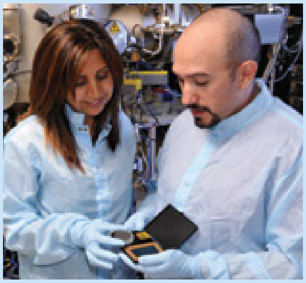
World Record Sensitivity with Solid-State Photon-Counting Arrays in Far Ultraviolet



We have demonstrated imaging arrays with >50% external QE in the FUV using MBE for delta doping and ALD for advanced antireflection coatings. This QE is about an order of magnitude higher than the GALEX detector and sets an unprecedented high sensitivity in this very challenging part of the spectrum. Another significant accomplishment has been the demonstration of delta-doped electron-multiplied CCDs (EMCCDs) by performing end to end post-fabrication back-illumination processing including thinning, delta doping, antireflection coatings, packaging, and characterizing fully fabricated e2v's low light level CCDs (L3CCDs). The delta-doped L3CCDs exhibited near 100% internal QE, indicating that the only loss of photons is due to the reflection from the back surface of the device. Adding the antireflection coatings to this device, we have demonstrated >50% QE using advanced AR-coating for the 100–300 nm spectral range. The combination of high QE and photon counting makes it possible to replace microchannel plate-based detectors that were used in GALEX and enable imaging and spectroscopy for exciting new missions.

MDL's Alex Carver at the newly installed custom-built MBE.

8-inch Silicon Molecular Beam Epitaxy for High Throughput Processing of UV/Optical/NIR Silicon Imaging Arrays



Above: Shouleh Nikzad mentors Todd Veach from Arizona State University. In our efforts, we involve students through university collaborations.

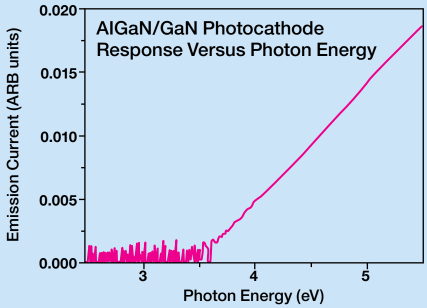
The current golden age of astronomy dictates design, fabrication, and deployment of large telescopes with large focal planes. To populate these large FPAs, a large number of high-performance detectors have to be produced. In these scientific applications, back illumination is crucial to achieve highest QE, highest fill factor, low dark current, and to extend the spectral range. JPL's delta-doping technology uses molecular-beam epitaxy (MBE) to modify silicon imagers and enable high QE and extended spectral response, as well as stability and uniformity required for precision photometry, high-resolution imaging, and spectrometry applications. JPL's large wafer capacity with multi-wafer capability provides high throughput processing required for producing a large number of large-area arrays to populate future large FPAs. One mission concept with very large FPAs is the Star Formation Observatory (SFO, Principal Investigator: Paul Scowen, Arizona State University). The SFO concept has two FPAs, each requiring over 200 high-sensitivity, large-format, science-grade CCDs.

Custom Back-illumination Processes for High-Performance CMOS Imagers

Custom end-to-end post-fabrication processes employing JPL's delta-doping technology were developed to produce back-illuminated high-performance CMOS and CCDs. A hybrid CMOS array designed at JPL (Cunningham et al., 389c), for example, requires hybridization to a thinned detector membrane. The capability to hybridize ultra thinned membranes to a readout array is a unique capability that is enabled using JPL's delta-doping technology and thereby achieving high QE and low dark current in this CMOS array.

In collaboration with Rochester Institute of Technology and University of Rochester, we have embarked on development of back-illuminated, thinned, delta-doped CMOS imagers for planetary applications. These detectors are fabricated using shared foundry runs and die-level thinning was necessary. A new approach to thinning with higher throughput and good uniformity was devised.

Stable Solar-Blind Ultraviolet Photocathodes *without* Cesiation



Above: The response of a prototype device starts at the band gap of gallium nitride and increases smoothly at higher energies.

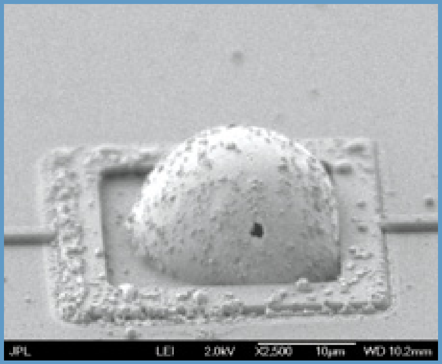
We are developing solar-blind photocathodes for ultraviolet detector applications, using intrinsically solar-blind gallium-nitride-based materials. Photocathodes absorb incoming light and emit photo-excited electrons from the device surface. When paired with microchannel plates or electron bombarded CCDs, they enable solar-blind UV imaging and photon counting detection.

While conventional photocathodes must be protected from air exposure in sealed vacuum tubes, we are developing air-exposable devices that will dramatically increase versatility and decrease cost. We use epitaxial techniques to exploit the natural high polarization and piezoelectricity of the gallium nitride semiconductor family in order to cause changes in the band structure and allow activation of these photocathodes.

MDL's Frank Greer working on ALD-deposited anti-reflection coatings with silicon imagers.

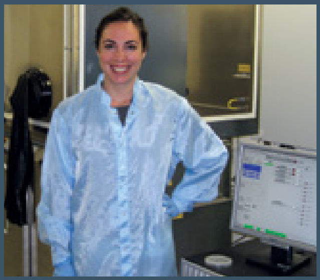
High Efficiency Solar-Blind UV III-Nitride Imaging Arrays

Large-bandgap semiconductors such as gallium nitride and its alloys are excellent candidate materials for fabricating solar-blind UV detectors. Previously, we have demonstrated interface-engineered p-i-n GaN detector designs with high quantum efficiency and low leakage. This year we focused on the development of nitride processing technologies, hybridization schemes, and materials screening infrastructure for the construction of large-format detector arrays. Indium bump reflow processes were developed for the optimization of our hybridization process. An array of rectangular indium bumps is exposed to a hydrogen plasma, and reflowed until the bumps assume a "tent"-like morphology on the underlying readout pads. The wetting between the indium and the under-bump metal-coated bond pad is substantially enhanced by the reflow process.

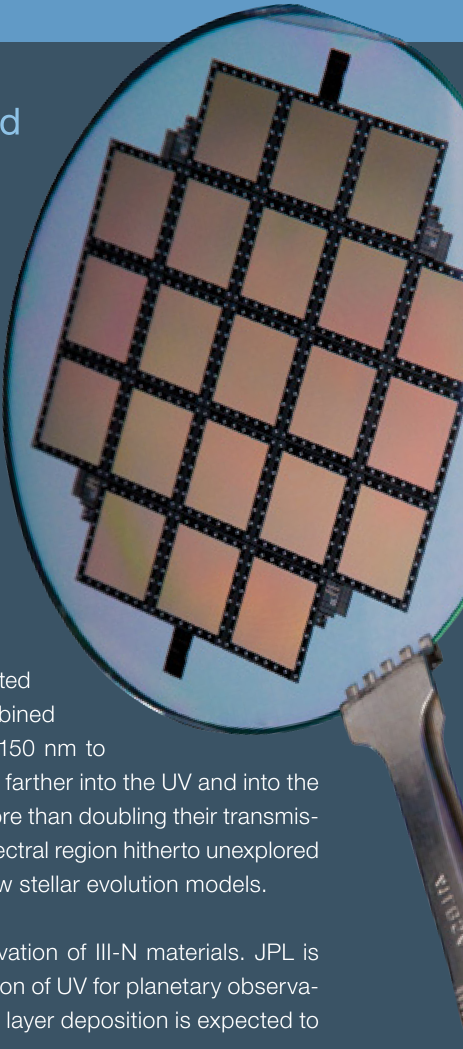


Above: SEM image of a reflowed indium bump.

Atomic Layer Deposition (ALD) for Detector, Optics, and Filters Fabrication and Enhancement


Above: Erika Hamden's work at MDL will contribute to her thesis as a graduate student from Columbia University.

Atomic layer deposition is a thin-film deposition technique where a desired film is grown using sequential surface reactions, one monolayer at a time. The properties inherent to the ALD method enable growth of high-quality, smooth, dense, pin-hole-free films with precise, angstrom-level thickness control over arbitrarily large surface areas. ALD is also well-suited for the growth of multilayer stacks of films with sharp interfaces. These characteristics of ALD make it ideally suited for fabrication of all types of optical elements, including mirrors, filters, and coatings, with the highest possible performance.

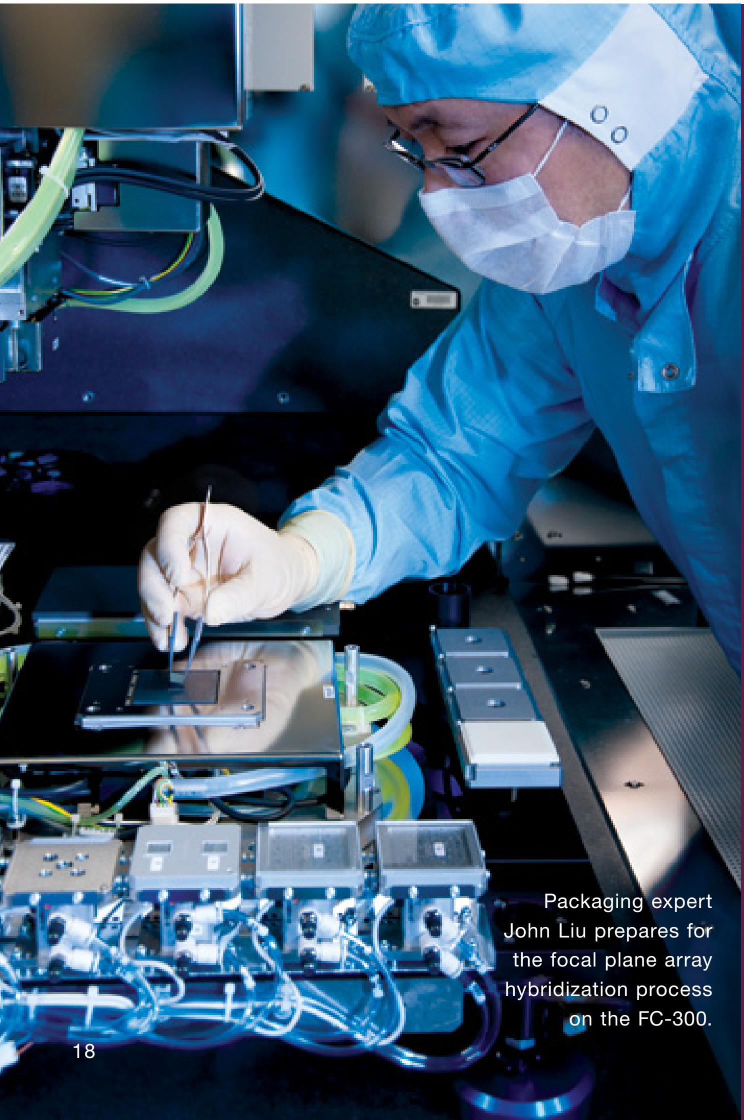


JPL has recently completed the world's first demonstration of direct integration of ALD-deposited anti-reflection coatings with silicon imagers. ALD of aluminum oxide and hafnium oxide combined with delta doping has produced world-record quantum efficiency in the ultraviolet from 150 nm to 300 nm. Future work in this area will be used to expand the range of ALD AR coatings both farther into the UV and into the visible. JPL has also dramatically improved the performance of FUV indium-based filters, more than doubling their transmission. This new JPL technology will enable a University of Colorado rocket flight to image a spectral region hitherto unexplored astronomically, potentially leading to the discovery of new quasars and development of new stellar evolution models.

In addition to ALD's applications for optical coatings, it is an excellent material for passivation of III-N materials. JPL is fabricating III-N pin diode arrays and III-N APDs for solar-blind and radiation-tolerant detection of UV for planetary observation and has obtained extremely low leakage (often below the detection limit of nA). Atomic layer deposition is expected to provide even better performance and enhance the stability of these detectors.

Infrared Photonics

The Infrared Photonics Technology Group (IRPTG) consists of 15 group members and is led by Dr. Sarath Gunapala. The IRPTG's main goal is to develop infrared technologies based on III-V compound semiconductor heterostructures. IRPTG is working 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 up to 8" wafers and are easier to grow and to process into large-area arrays.



Packaging expert John Liu prepares for the focal plane array hybridization process on the FC-300.

MDL is Trailblazing in Infrared Detection Technology

IRPTG is engaged in the development for quantum-well infrared photodetectors (QWIPs), quantum-dot infrared photodetectors (QDIPs), superlattice, barrier infrared detectors (BIRDs) and large-area focal plane arrays based on these detector technologies for NASA, defense, and intelligence applications. IRPTG has produced over 200 publications and 20 US and international patents on infrared detection technologies. Most of these patents are commercialized via the Caltech/JPL commercialization process to QWIP Technologies and Advanced BioPhotonics, Inc. It is also worth noting that the BioScan system jointly developed by the Advanced BioPhotonics and IRPTG was approved by the United States Food and Drug Administration for breast tumor detection in 2001. IRPTG has done many trailblazing demonstrations in infrared detection technology, including the demonstration of the highest-performing long-wavelength superlattice device CBIRD (complementary BIRD), the first demonstration of large-format QDIP focal planes, and the first demonstration of a dual-band simultaneous pixel co-registered megapixel QWIP focal plane. The latest addition to the IRPTG's instrument suite is the FC-300 large-area flip-chip bonder capable of hybridizing >4Kx4K pixels infrared focal plane arrays.

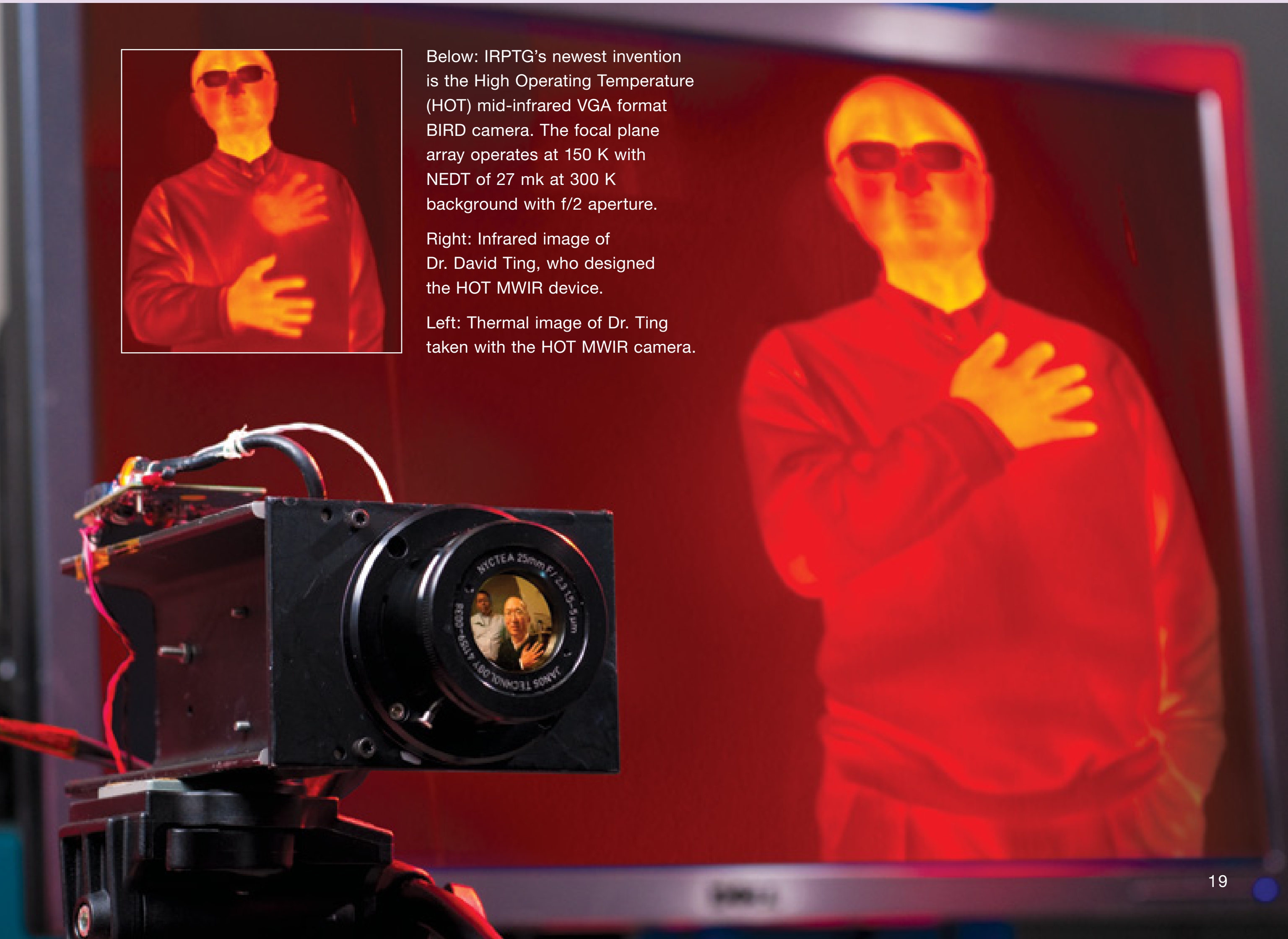
Breakthrough Development Enables the Use of High-Performance Infrared Instruments for Spaceborne Earth and Planetary Science Applications

IRPTG has developed a new barrier infrared detector (BIRD), based on III-V heterostructures, as an alternative to a homojunction photodiode. The main difference is that no depletion layer exists in any narrow bandgap region of the device. Instead, the depletion layer is confined to a wide-bandgap barrier material. The generation-recombination (G-R) dark current associated with mid-bandgap Shockley-Read-Hall G-R centers is almost eliminated and the dark current becomes diffusion limited. This lowering of dark current allows the BIRD operating temperature to be raised relative to that of a standard homojunction photodiode made from the same photo-sensitive material without loss of performance. We have developed BIRDs grown on GaSb substrates with lattice-matched InAsSb photo-sensitive layers and lattice-matched AlSbAs barrier layers in to VGA-format focal planes. We have demonstrated strong suppression of G-R currents at high operating temperatures as high as 150 K, which can be easily achieved passively in space. This breakthrough development enables the use of high-performance infrared instruments for spaceborne Earth and planetary science applications.

Below: IRPTG's newest invention is the High Operating Temperature (HOT) mid-infrared VGA format BIRD camera. The focal plane array operates at 150 K with NEDT of 27 mk at 300 K background with f/2 aperture.

Right: Infrared image of Dr. David Ting, who designed the HOT MWIR device.

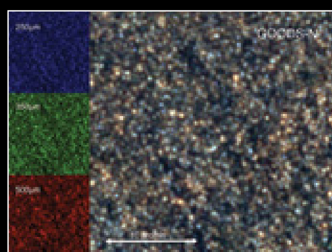
Left: Thermal image of Dr. Ting taken with the HOT MWIR camera.



Superconducting Materials and Devices

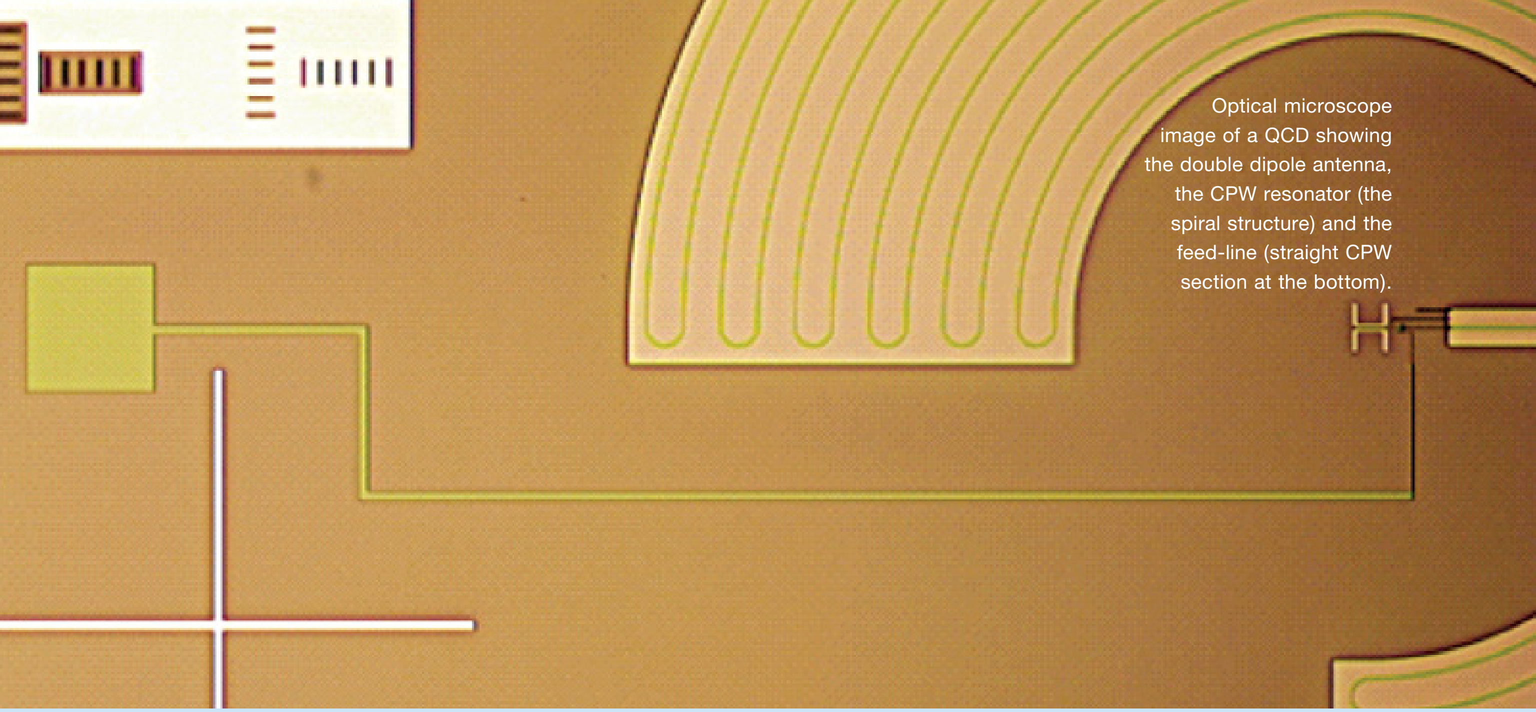
JPL's Superconducting Materials and Devices Group's primary focus is on cryogenic millimeter and submillimeter detectors for spectroscopy, imaging, and polarimetry measurements in astrophysics. JPL has been a pioneer in the development of superconducting detectors for far-infrared/submillimeter astrophysics for 25 years. Initially this effort focused on superconductor-insulator-superconductor (SIS) mixers for heterodyne receivers, for high-resolution spectroscopy. These mixers are in use for both ground-based telescopes around the world, as well as current and future planned NASA flight missions. More recent development efforts have been on large-format arrays of direct detectors for spectroscopy, imaging, and polarimetry.

First Images from Herschel SPIRE and the Planck High Frequency Instrument



Above: A false-color image is shown of thousands of distant, luminous, unresolved galaxies as seen by SPIRE. Color coding information indicates the temperatures and distances of the galaxies. Images courtesy of ESA and the HerMES consortium.

Nearly 15 years ago, work started at JPL in the superconducting devices group on two instruments on ESA-led missions: the SPIRE instrument for the Herschel space telescope *(shown left)* and the High Frequency Instrument (HFI) on the Planck telescope. Currently in orbit, Herschel and Planck were launched on May 14, 2009. The instruments on Herschel, including SPIRE, "point and shoot" at scientifically interesting objects in the sky to achieve very high sensitivity images. JPL's contribution to Herschel's SPIRE instrument consisted of fabrication and testing of flight bolometer arrays with 50–100 detectors each, suspended by a low-thermal-impact support structure. JPL also delivered a cryogenically operated JFET preamplifier and the bias circuit. The Planck satellite observes the sky in a different manner. It spins on an axis mapping out large circles on the sky. As Planck orbits the Sun, the spin axis of Planck precesses, mapping a new circle approximately every hour. After 6 months, Planck obtains a complete map of the sky. The JPL contribution for Planck HFI was similar to that for SPIRE; however, each of the 54 bolometers in the focal plane were assembled in individual packages and 32 of the 54 bolometers were sensitive to a single polarization.

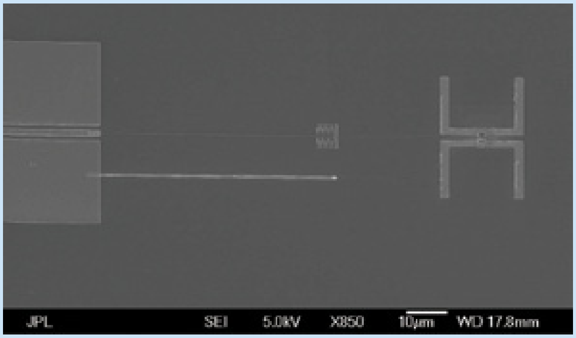


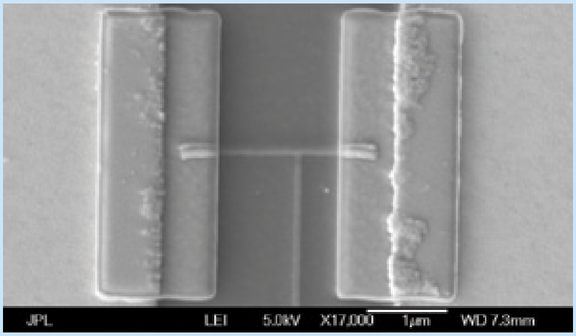
Optical microscope image of a QCD showing the double dipole antenna, the CPW resonator (the spiral structure) and the feed-line (straight CPW section at the bottom).

Successful Test of Prototype Quantum Capacitance Detector

The quantum capacitance detector (QCD) is a new concept for a photo-detector based on Cooper-pair breaking in superconductors using a single Cooper-pair box (SCB) as a readout. In this concept, antenna-coupled radiation breaks Cooper pairs in a superconducting absorber and the unpaired electrons then tunnel to an SCB embedded in a resonator. The unpaired electrons change the capacitance of the SCB, and hence the resonant frequency of the resonator, which is read out by RF techniques. The applications would be similar to MKIDs and TES detectors. QCDs combine the sensitivity of TESs and the simplified readout of MKIDs, i.e., arrays can be frequency multiplexed and readout with a single RF line and do not require individual bias of each pixel.

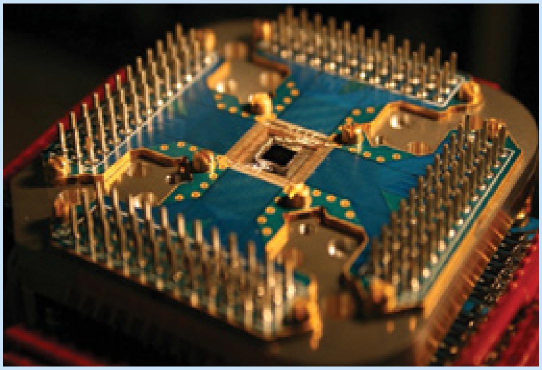
In 2010, a first prototype achieved an optical noise equivalent power of 1×10^{-17}W/Hz$^{1/2}$. In this prototype, radiation generated by a blackbody source and filtered around a wavelength of 200 μm was focused by a silicon hyper-hemispherical lens onto a double-dipole antenna lithographed on chip. The antenna coupled the radiation to an aluminum absorber with niobium banks where the unpaired electrons were trapped. The absorber acted as the ground plane for an SCB, which was coupled to a niobium coplanar waveguide (CPW) resonator. A CPW feed-line coupled to the resonator was used to couple the RF signal to the resonator, and the phase of the transmitted RF was used to measure the capacitance of the SCB.





Above left: The coupling capacitor. Right: The absorber with Nb banks.

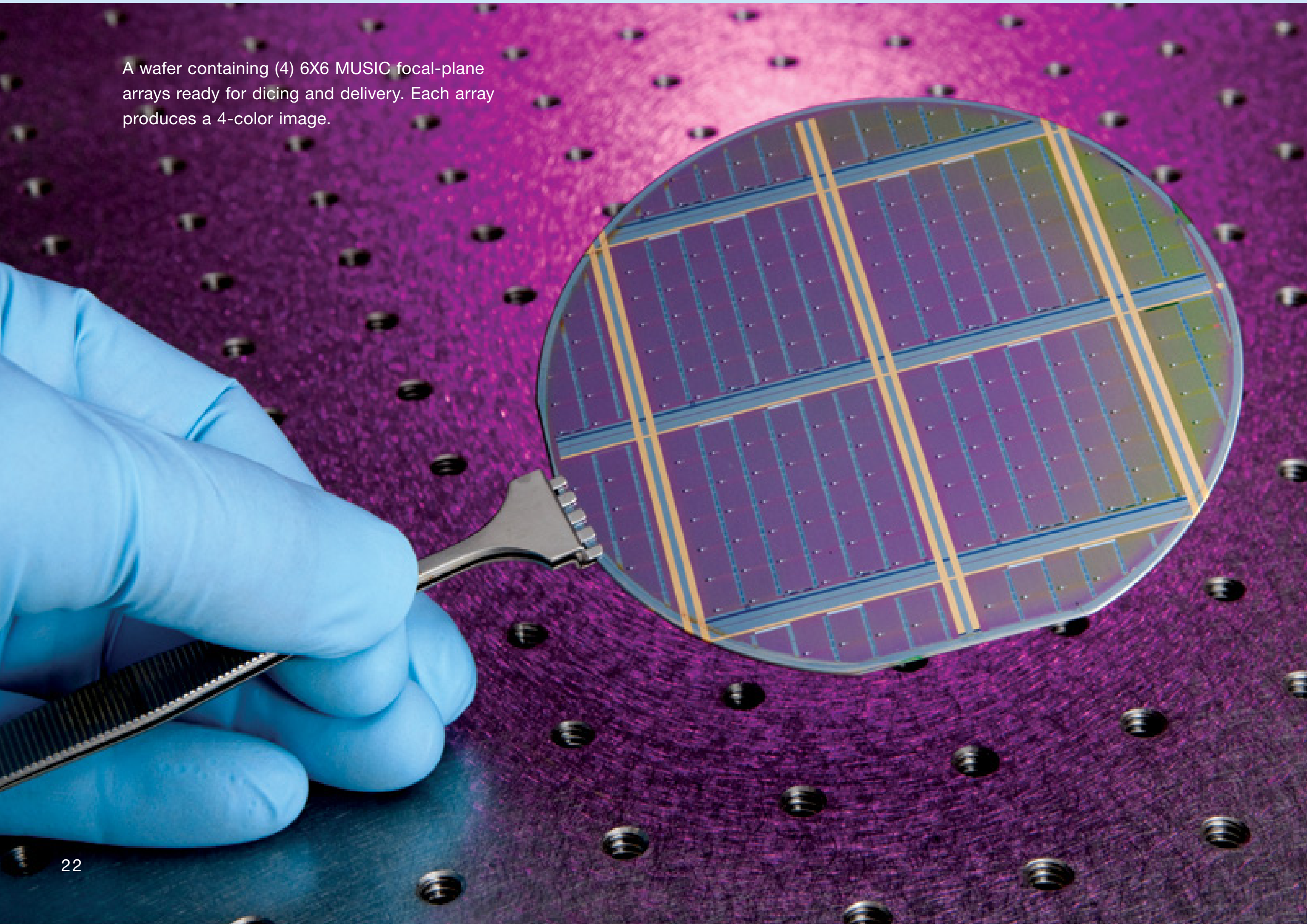
Superconducting Integrated Circuits for Advanced Computing



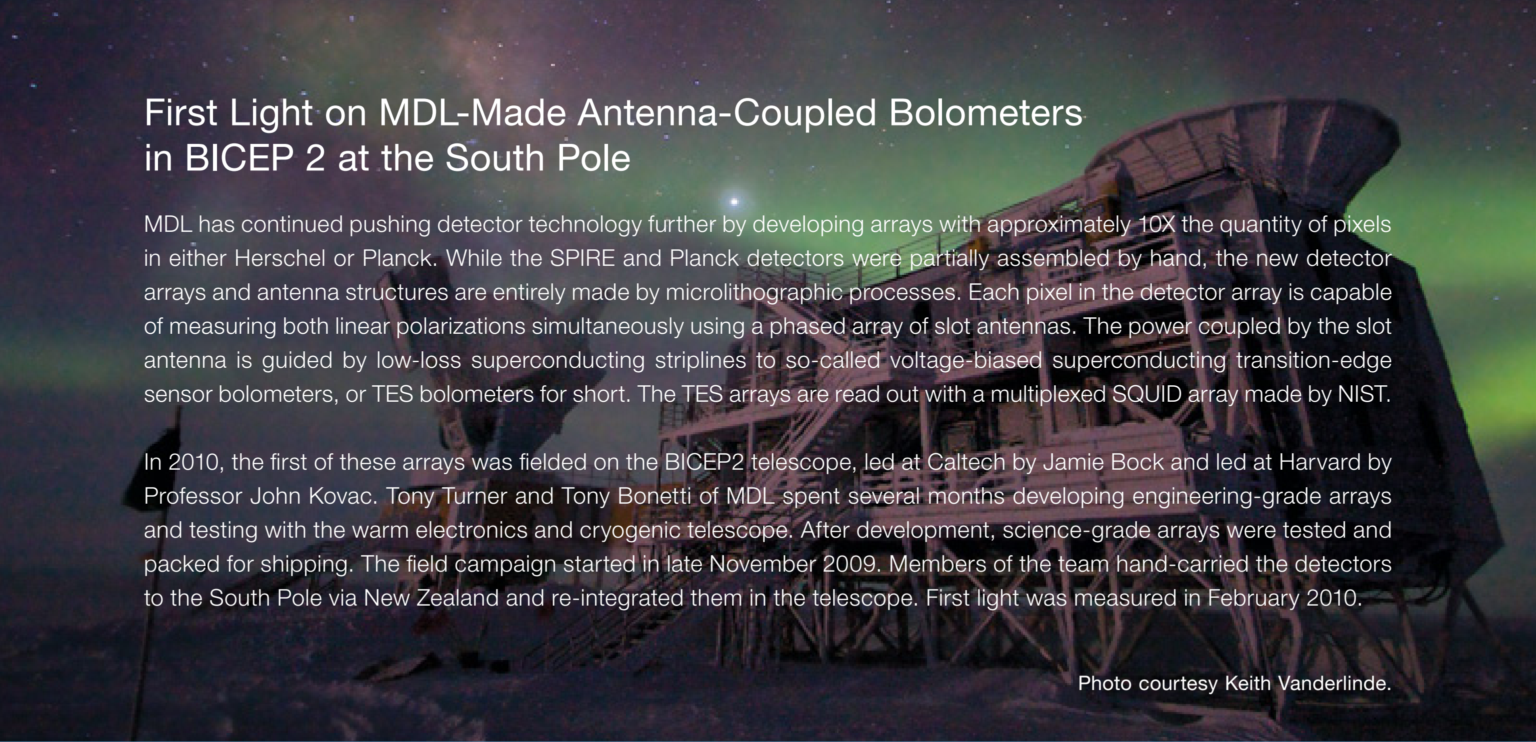
Above: Adiabatic quantum processor chip mounted in cryogenic chip carrier and ready for use.

MDL continues to leverage its decades of experience with superconductor sensors to participate in the advancement of adiabatic quantum computation (AQC) by teaming with D-Wave Systems Inc.

D-Wave has achieved impressive results in mapping combinatorial optimization problems onto two-dimensional arrays of superconducting quantum interference devices (SQUIDs) and exploiting quantum effects to achieve dramatic speedup of calculations and improvement of solution accuracy. For several years, MDL was the exclusive source of D-Wave chips. Recently, D-Wave has developed a state-of-the-art manufacturing capability and MDL has transitioned to an R&D role, attacking problems related to decoherence, power reduction, and device physics, prototyping new circuit concepts, and supporting and advancing its fabrication process.



A wafer containing (4) 6X6 MUSIC focal-plane arrays ready for dicing and delivery. Each array produces a 4-color image.



First Light on MDL-Made Antenna-Coupled Bolometers in BICEP 2 at the South Pole

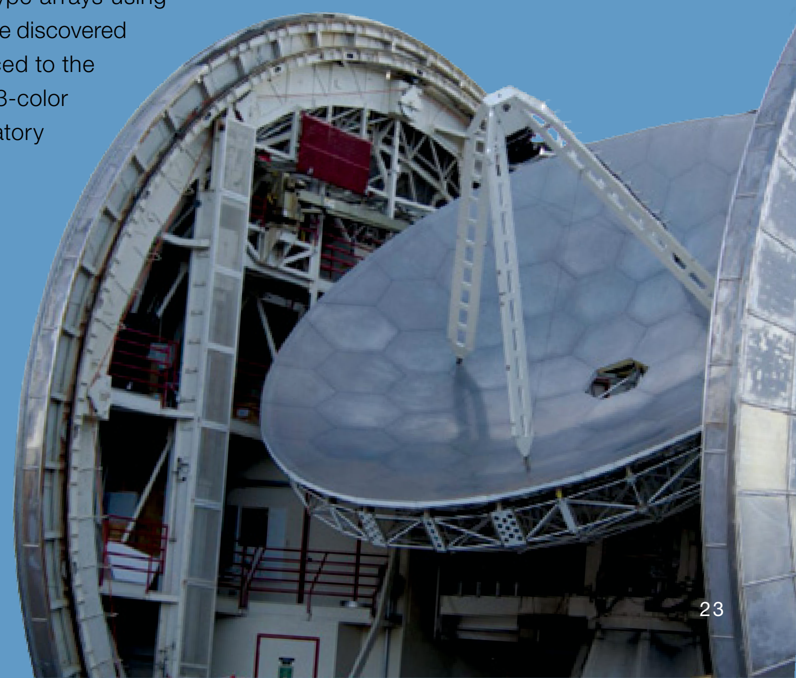
MDL has continued pushing detector technology further by developing arrays with approximately 10X the quantity of pixels in either Herschel or Planck. While the SPIRE and Planck detectors were partially assembled by hand, the new detector arrays and antenna structures are entirely made by microlithographic processes. Each pixel in the detector array is capable of measuring both linear polarizations simultaneously using a phased array of slot antennas. The power coupled by the slot antenna is guided by low-loss superconducting striplines to so-called voltage-biased superconducting transition-edge sensor bolometers, or TES bolometers for short. The TES arrays are read out with a multiplexed SQUID array made by NIST.

In 2010, the first of these arrays was fielded on the BICEP2 telescope, led at Caltech by Jamie Bock and led at Harvard by Professor John Kovac. Tony Turner and Tony Bonetti of MDL spent several months developing engineering-grade arrays and testing with the warm electronics and cryogenic telescope. After development, science-grade arrays were tested and packed for shipping. The field campaign started in late November 2009. Members of the team hand-carried the detectors to the South Pole via New Zealand and re-integrated them in the telescope. First light was measured in February 2010.

Photo courtesy Keith Vanderlinde.

Developments at JPL for MUSIC

MUSIC (MUltiband Submillimeter Inductance Camera) is a camera based on kinetic inductance detectors (KIDs). The instrument is sponsored by the National Science Foundation and is being built by a consortium of astronomers from the University of Colorado and Caltech. At completion, the focal plane will consist of an array of 576 pixels (24x24), simultaneously imaging in four bands at 2 mm, 1.36 mm, 1.03 mm, and 0.85 mm for a total of 2304 channels. At MDL, we are developing detector array technology suitable for the MUSIC instrument. To achieve the large bandwidth required for 4-color operation, each pixel consists of a periodic array of long slot antennas periodically tapped by microstrip couplers and a binary tree power combiner. This arrangement forms a synthesized antenna with a well-defined beam without the need for fore-optics. We have also fabricated 6x6 prototype arrays using several spatial distributions of resonant frequencies and have discovered that inter-pixel coupling in the readout band can be reduced to the required level for operation. One of the prototype arrays (a 3-color version) was taken to the Caltech Submillimeter Observatory *(pictured right)* for a test run with favorable results.



To further optimize the detector performance, we are studying lower-loss dielectrics for our antenna power microstrip combiner (currently silicon dioxide (SiO_2)). We have fabricated prototype arrays using ICP-PECVD grown SiN_X as a replacement for the dielectric on the microstrip power combiner. With this prototype array, we will be able to measure the millimeter-submillimeter wave index and loss of the SiN_X and test the redesigned bandpass filters. These devices are currently under test. The full MUSIC instrument is expected to be fielded in the summer of 2011.

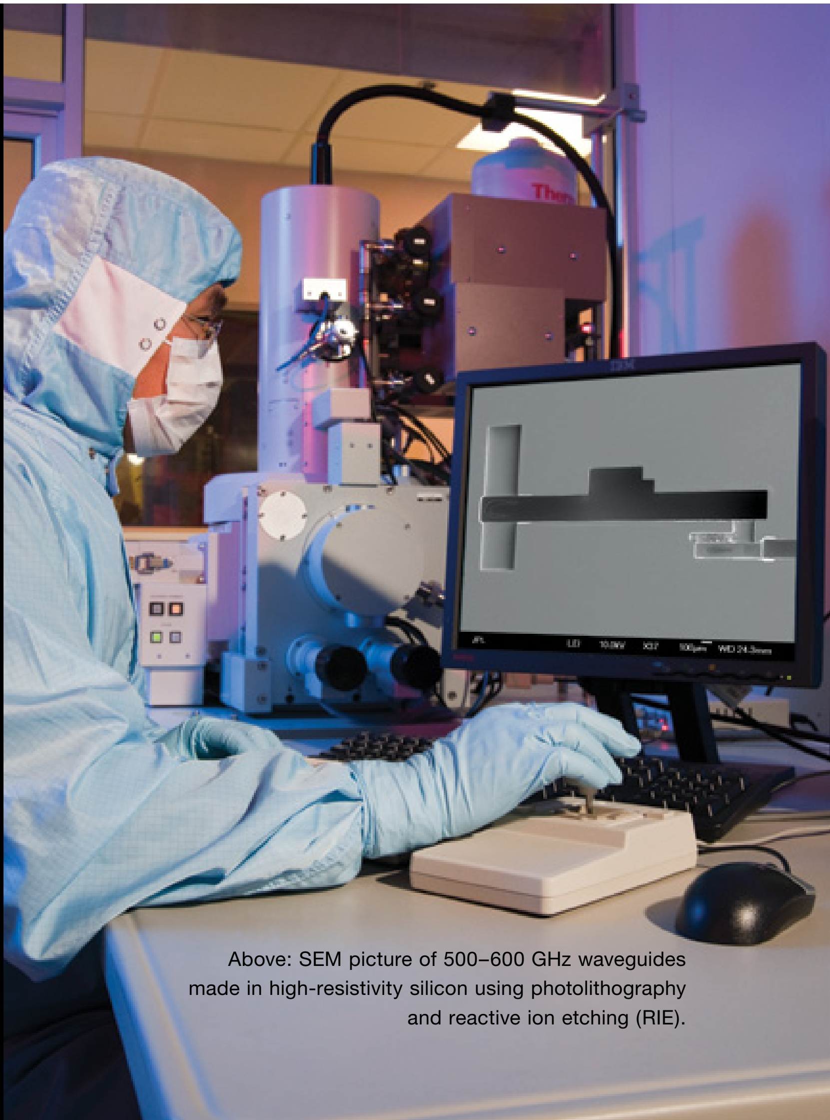
Submillimeter-Wave Advanced Technologies

The Submillimeter-Wave Advanced Technology (SWAT) Group specializes in developing and implementing submillimeter-wave and terahertz remote sensing technologies for a variety of applications. The group's 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. The group'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.

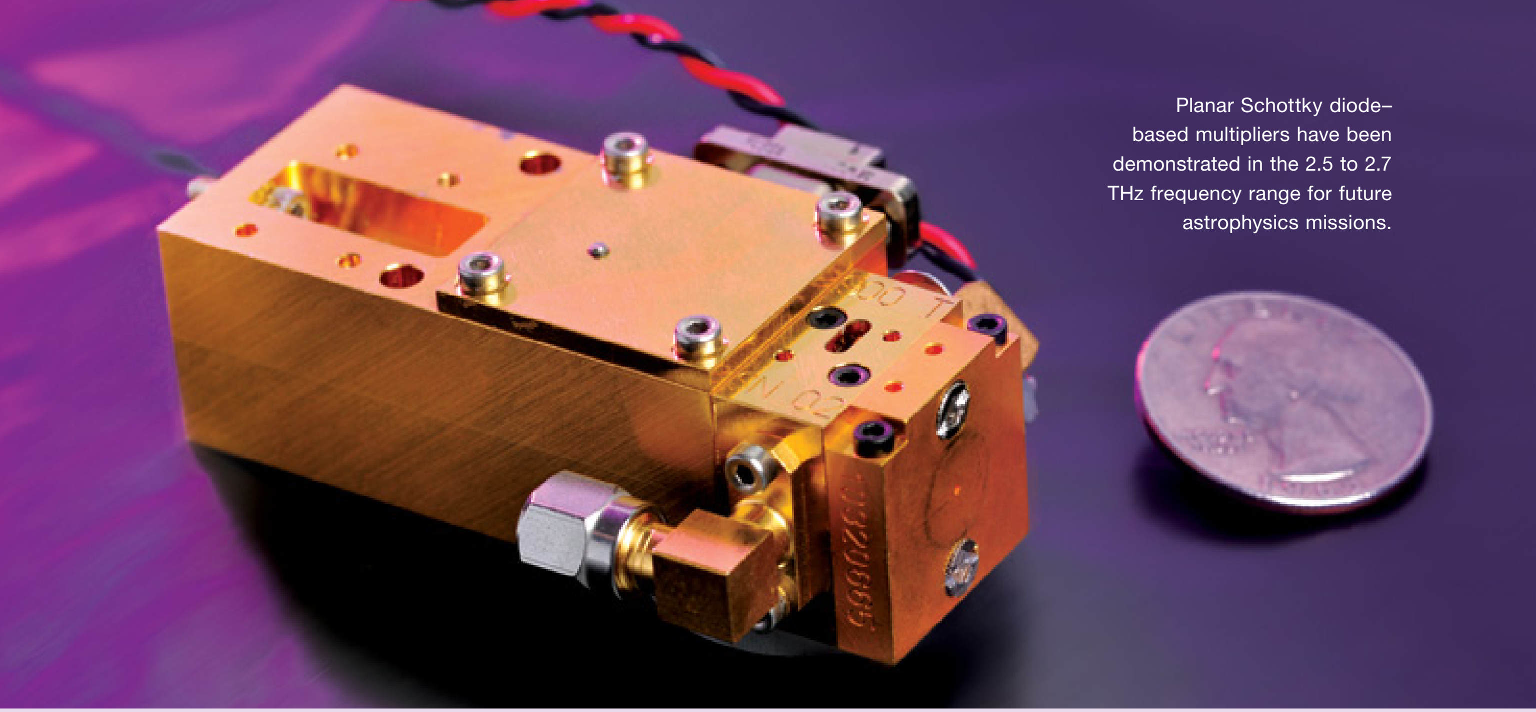
Silicon Micromachining of THz Components

Submillimeter heterodyne instruments play a critical role in addressing fundamental questions regarding the evolution of galaxies and interstellar clouds, while enhancing our understanding of planet Earth by providing remote sensing data on the higher troposphere and lower stratosphere. However, to make these instruments compatible with small platforms, especially for the study of the outer planets, or enable the development of multi-pixel arrays, it is essential to reduce the mass, power, and volume of existing single-pixel heterodyne receivers.

At JPL, we have developed world-class expertise in fabricating GaAs Schottky diode–based integrated circuits for submillimeter and THz applications. Normally, the mixer and the multiplier chips are packaged in separate waveguide blocks and then connected to form the receiver front end. One way to make supercompact receiver front ends is to etch the waveguide and channel cavities in silicon bulk material, and to integrate the power amplifiers, multiplier, and mixer chip in a single silicon micromachined block.

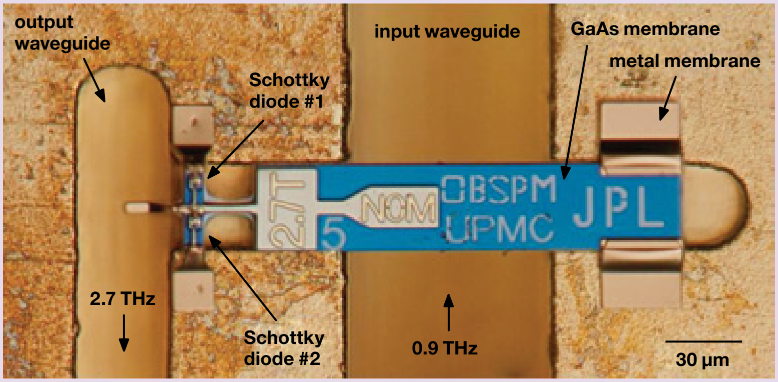


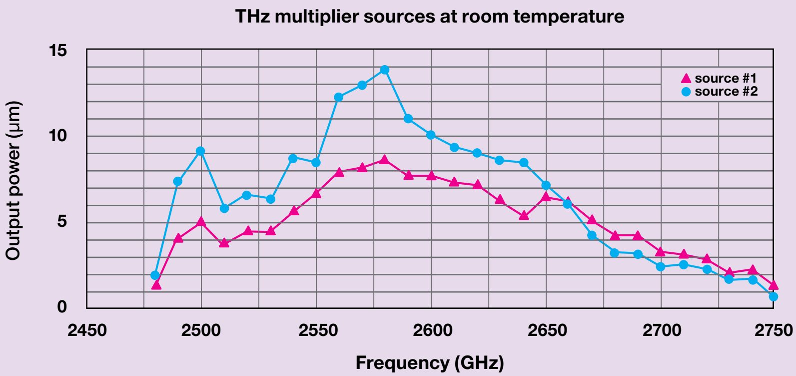
Above: SEM picture of 500–600 GHz waveguides made in high-resistivity silicon using photolithography and reactive ion etching (RIE).



Planar Schottky diode–based multipliers have been demonstrated in the 2.5 to 2.7 THz frequency range for future astrophysics missions.

MDL Demonstrates that Purely Electronic Solid-State Sources Can Generate Useful Amounts of Power in a Region of the Electromagnetic Spectrum Where Lasers Were Once Considered the Only Logical Source

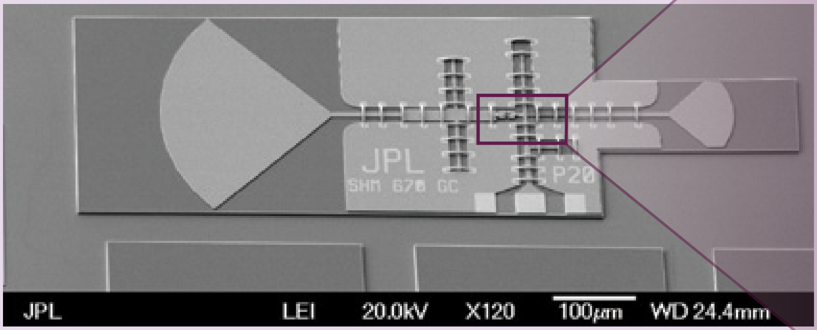




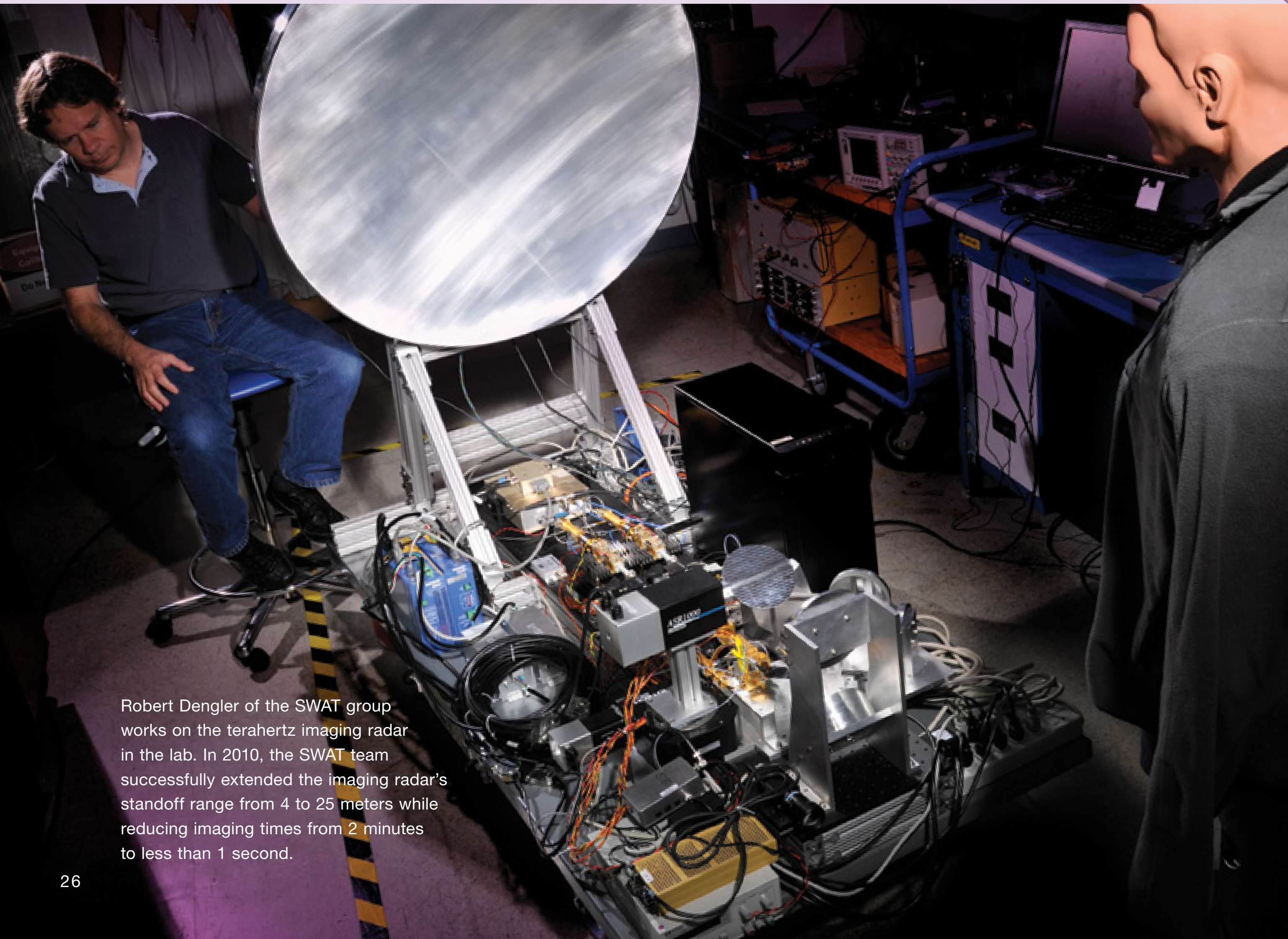
We have demonstrated a continuous wave (CW) coherent source covering 2.48–2.75 THz, with greater than 10% instantaneous and tuning bandwidth and having 1–14 µW of output power at room temperature. This source is based on a 91.8–101.8 GHz synthesizer followed by a power amplifier and three cascaded frequency triplers. It demonstrates for the first time that purely electronic solid-state sources can generate a useful amount of power in a region of the electromagnetic spectrum where lasers (solid state or gas) were previously the only available coherent sources. The bandwidth, agility, and operability of this THz source has enabled wide-band, high-resolution spectroscopic measurements of water, methanol, and carbon monoxide with a resolution and signal-to-noise ratio unmatched by any other existing system, providing new insight into the physics of these molecules.

A New Collaboration to Develop Integrated Planar Mixers

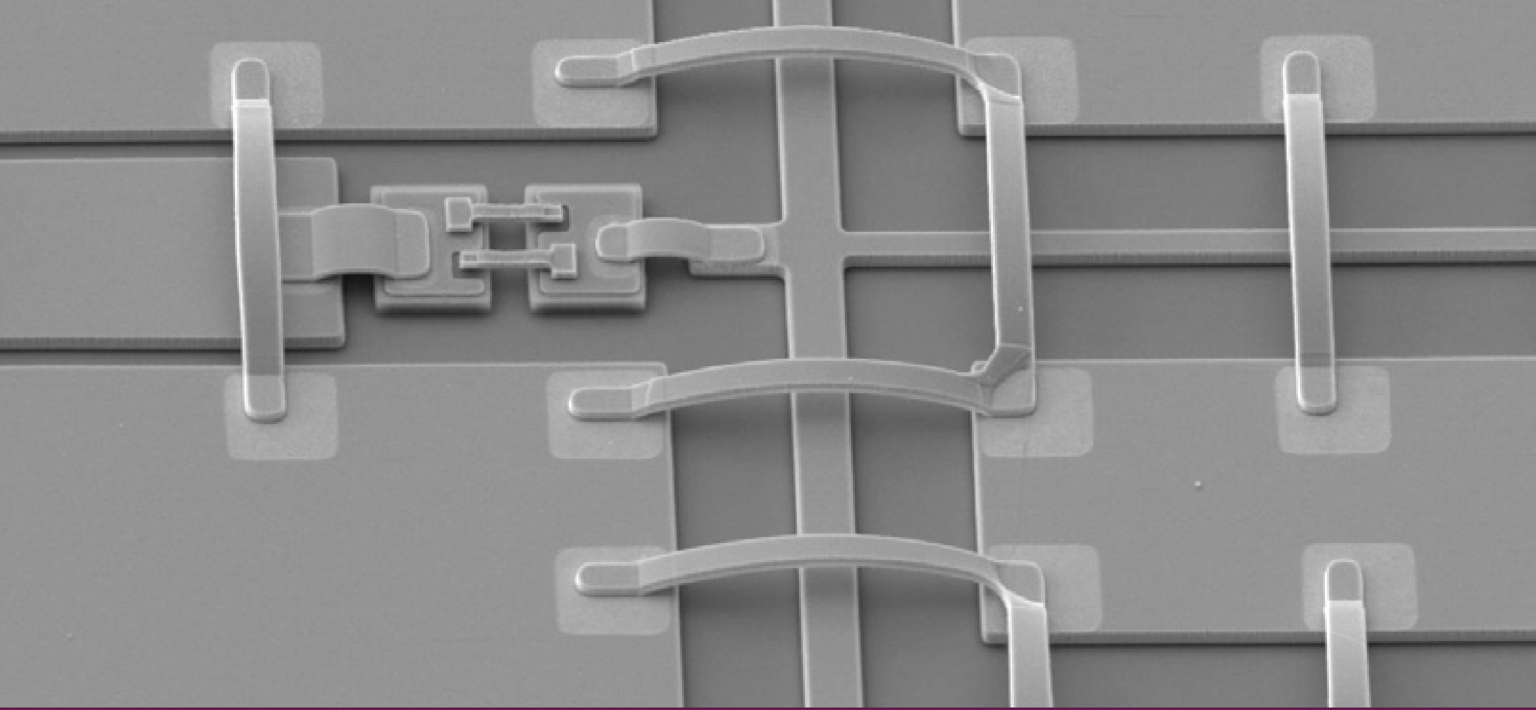
JPL, in collaboration with Northrop Grumman, is developing planar GaAs-based mixers and multipliers working at 670 GHz to be integrated with amplifiers under the DARPA Terahertz Transistor and Imaging Program. This represents the first wafer-bonded all-planar mixers and amplifiers for a 670-GHz receiver system.



Above: SEM picture of the mixer MMICs fabricated at JPL's MDL at 100 μm.
Right: SEM detail of the mixer MMICs at 10 μm.



Robert Dengler of the SWAT group works on the terahertz imaging radar in the lab. In 2010, the SWAT team successfully extended the imaging radar's standoff range from 4 to 25 meters while reducing imaging times from 2 minutes to less than 1 second.



MDL Makes Rapid Progress on Navy-Funded Effort to Detect Concealed Weapons and Contraband at Long Standoff Ranges

The Submillimeter-Wave Advanced Technology (SWAT) team continued to make rapid progress under its Navy-funded terahertz imaging radar program in FY2010. The imaging radar is being developed to detect person-borne concealed objects at long standoff ranges. Terahertz frequencies are needed to accomplish this because the diffraction-limited image resolution is high for the submillimeter wavelengths, while the signal attenuation from clothing is not too large. In addition, the huge bandwidth available at terahertz frequencies leads to unprecedentedly high range resolution, so that three-dimensional target discrimination can be made between clothing layers and concealed objects. A terahertz frequency multiplier and mixer, fabricated in the JPL Microdevices Laboratory, comprise some of the key elements of the imaging radar's receiver module. In FY2010, the SWAT team extended the imaging radar's standoff range from 4 to 25 meters, and also reduced the time required to obtain an image from over 2 minutes to less than 1 second. Under continuing Phase 4 funding, a prototype instrument will be delivered to the Navy for government evaluation in mid-2011.

Above: Through-clothes detection of a concealed weapon. **A)** A mock pipe bomb approximately 30 cm long. **B)** The mock bomb is then strapped to the torso, and **C)** concealed by a jacket. **D)** Through-clothes radar imagery revealing a concealed mock pipe bomb.

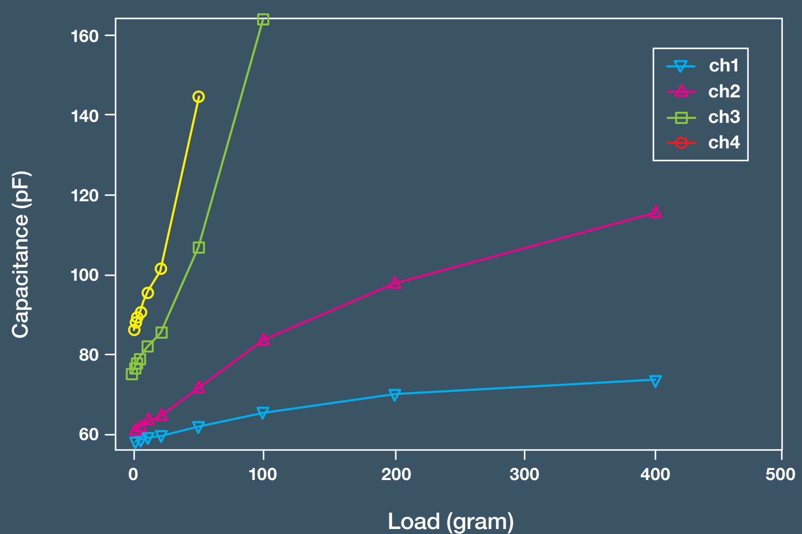
Nano and Micro Systems

Nano and Micro Systems continues to be a predominantly technology development group with an active effort in recent times to transition some of our technologies into flight. One of the technologies developed to make black silicon using a cryo-etching process is being used as optical absorbers for imaging spectrometer applications through a joint collaboration with the Advanced Microfabrication and Optoelectronics Group. Another technology is the development of a sample mass verification sensor based on distributed capacitive sensing for future sample return missions to the Moon, Mars, and small bodies (asteroids and comets). In addition to these, technology development projects in carbon nanotube devices, GaN devices, and advanced miniature tools for stereo imaging for medical and planetary exploration are continuing. A new project to develop CNT-based electron-beam-pumped mid-UV lasers for high-sensitivity trace element fingerprinting is also beginning this year.

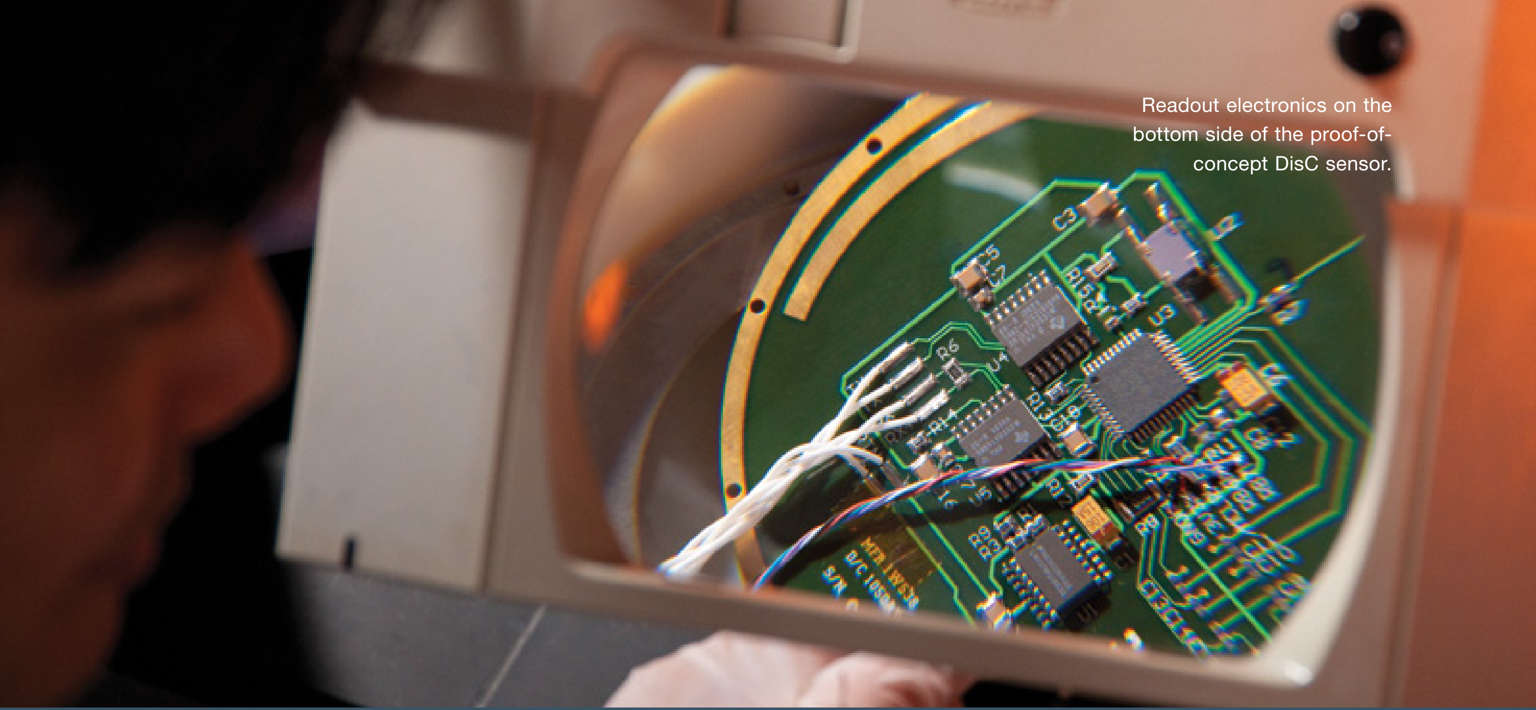
In Situ MEMS Sample Verification Sensor System Developed for Future Sample Return Missions

A MEMS sample verification sensor system (SVS) has been developed for in situ mass measurement of planetary rock and soil samples during future robotic sample return missions. Past robotic sample return missions such as the Russian Luna, NASA's Genesis and Stardust, and JAXA's Hayabusa missions did not have an in situ sample acquisition verification system. As a result, confirmation of successful sample acquisition could only be done after the return of the sample capsule to Earth. The in situ SVS would enable the unmanned spacecraft system to positively confirm the acquisition of the desired sample quantity prior to its return.

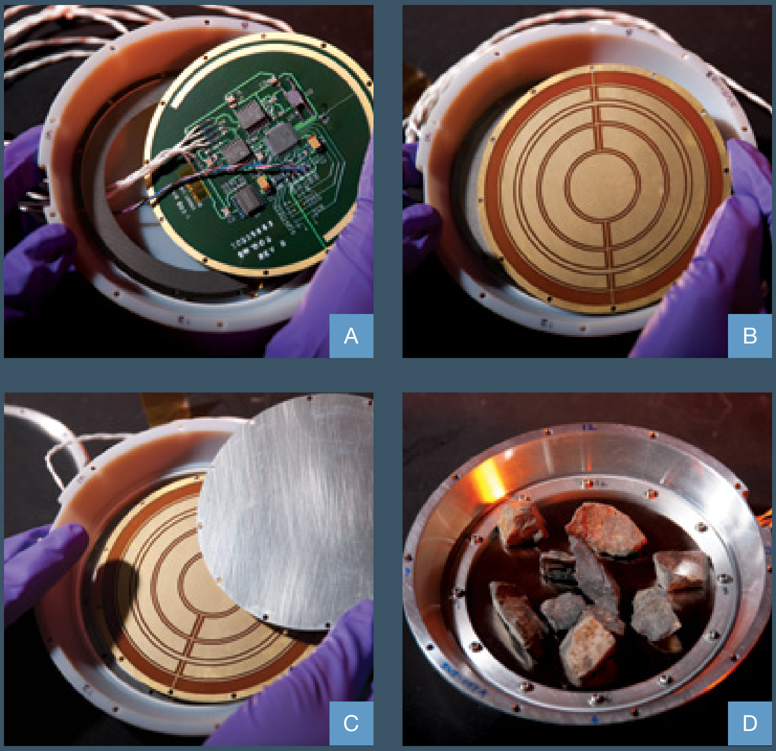
The SVS contains a 10-cm-diameter distributed capacitive sensor or the DisC sensor, comprising of a pressure-sensitive elastic membrane at the top fixed in close proximity to an electrode-patterned bottom substrate. This forms a parallel plate capacitor with multiple segmented electrodes. When placed at the bottom of a sample canister, the top membrane deforms under the weight of an accumulating planetary sample, thus changing the capacitance of the sensor proportional to the sample mass (right). The concentric distributed capacitor design divides the overall sample weight measurement range into discrete steps that can be then be



Above: Graph showing the variation of capacitance of segmented electrodes with respect to changing load.



Readout electronics on the bottom side of the proof-of-concept DisC sensor.

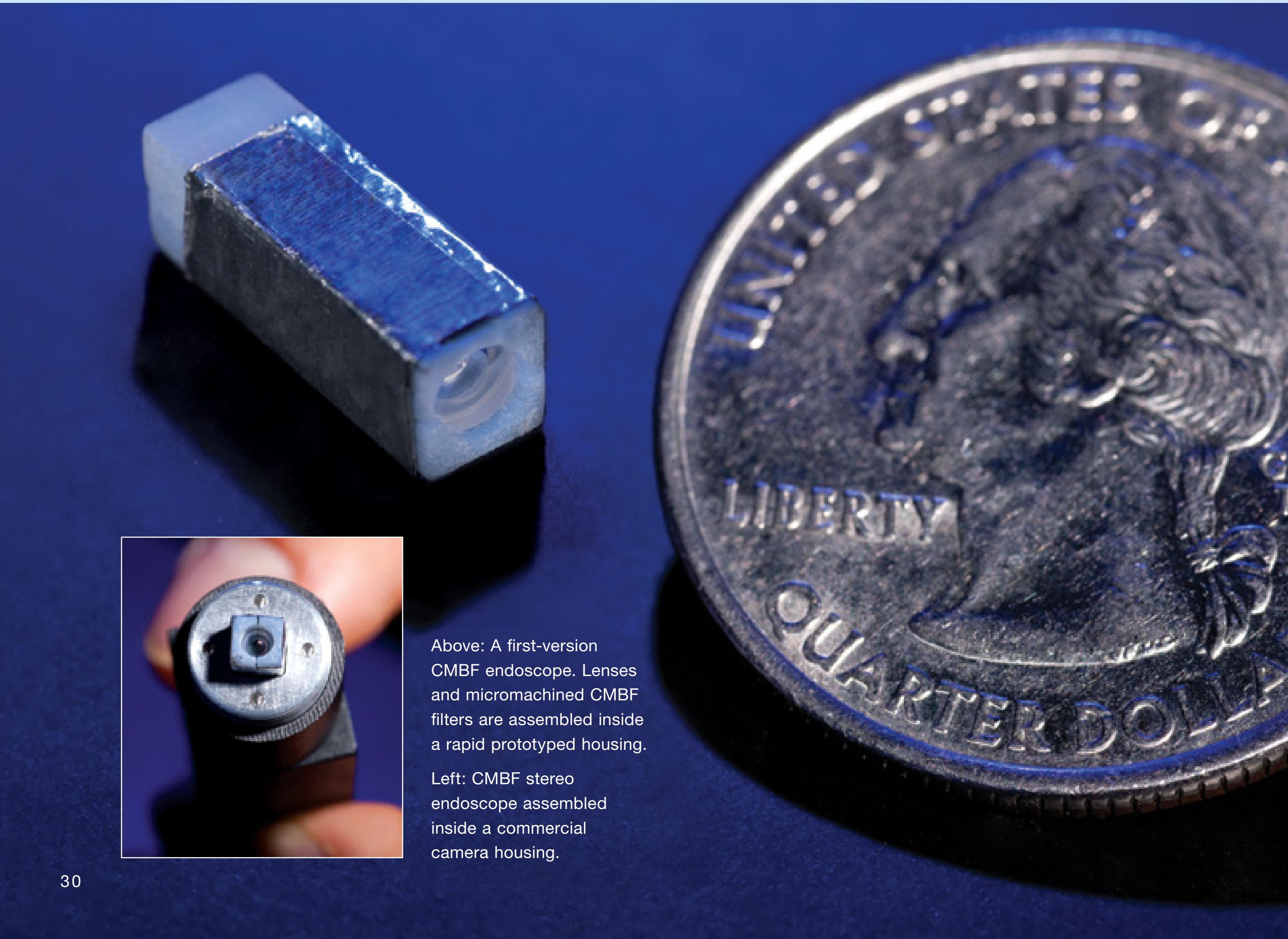


Above: Step-by-step assembly of process of the DisC sensor inside a sample canister part. **A)** Bottom side of the DisC sensor containing readout electronics, **B)** Top side of the DisC sensor showing patterned distributed capacitors, **C)** Assembly showing the top metal plate over patterned capacitors, **D)** Fully assembled DisC sensor inside a sample canister part measuring the mass of rock samples.

identified as baseline, minimum, mission target, and maximum. The sensor is designed to be inherently robust against shock as a rigid bottom substrate prevents the top membrane from overstressing. This sensor stack forms the false bottom of a sample canister. It is fastened to the canister bottom using pressure-loaded fasteners, which also help mitigate thermal stresses by accommodating relative dimensional changes of the assembly due to CTE mismatch under large temperature variation. At the back of the sensor substrate, a capacitance readout electronics PCB is integrated that transmits change in capacitance data via a low-voltage differential signaling (LVDS) interface. The sensor is designed to prevent sample contamination. The proof-of-concept sensor has shown high sensitivity of 1pF/gram at low mass range while maintaining capability to measure large mass, in excess of 1,500 grams. This development is a joint effort between MDL and the Robotics section within JPL.

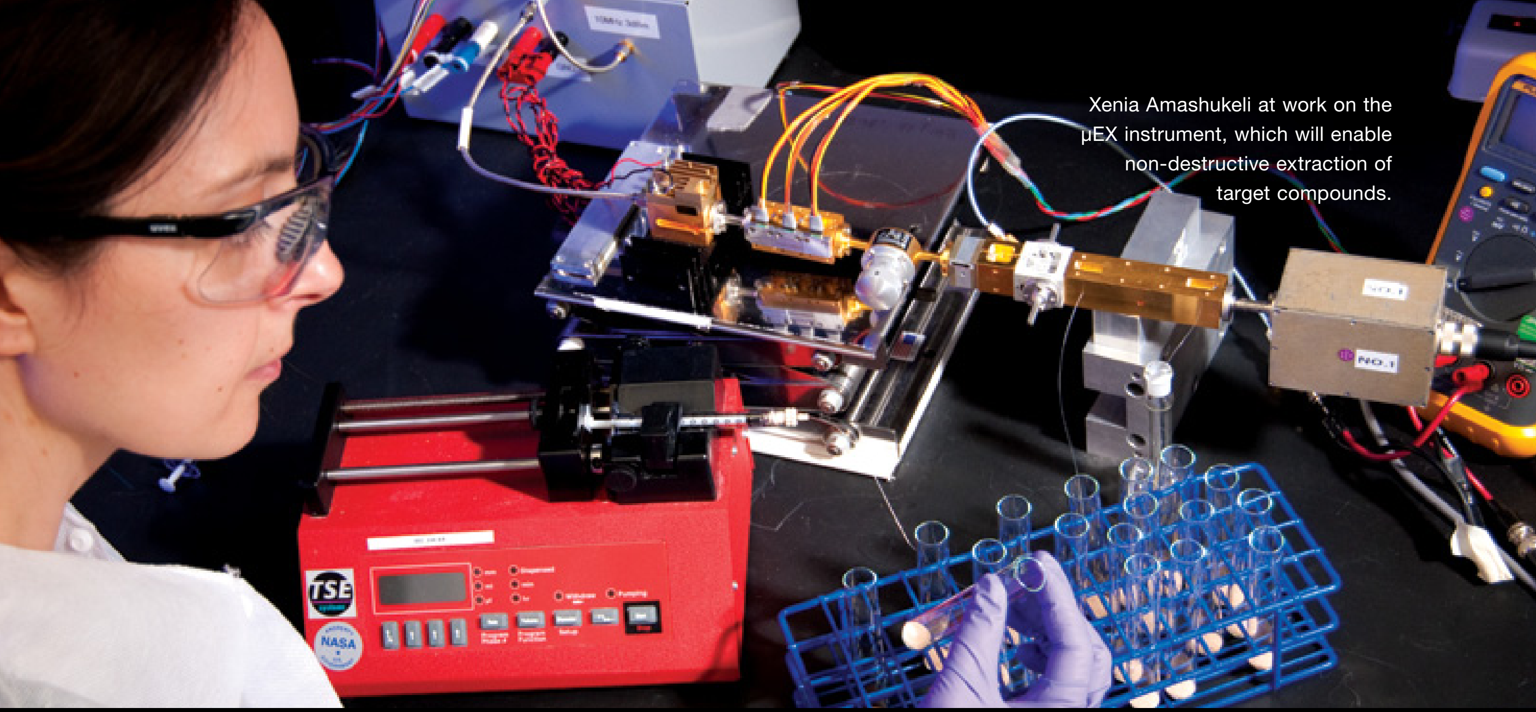
A Novel Stereo Imaging Miniature Endoscope Using Single Objective for Minimally Invasive Surgeries and Planetary Exploration

In collaboration with the Skull Base Institute, JPL has developed a new technology for stereo imaging using a single objective and two complementary multi-bandpass filters (CMBF). The first demonstration was performed using commercial-off-the-shelf (COTS) lenses and multi-bandpass filters micromachined at MDL. These optical elements were integrated inside a 4-mm-diameter, rapid prototyped plastic housing. A COTS imager of 640x480 resolution (6.0 micrometer square pixels) from a commercial camera was used to capture stereo images. This is a first-time demonstration of CMBF technique that has the potential to capture high-resolution (1080x1080) stereo images with custom-designed optics. One of its potential applications includes 3D endoscopes for minimally invasive surgery (MIS), for studies have shown that better depth perception leads to better hand-eye coordination during surgery. MDL's stereo endoscope would allow for 3D stereo imaging within the same volume afforded by a 2D endoscope currently employed in skull base and brain surgery. It also can also be used as a miniature stereo camera for in situ investigation of geological features during planetary exploration.



Above: A first-version CMBF endoscope. Lenses and micromachined CMBF filters are assembled inside a rapid prototyped housing.

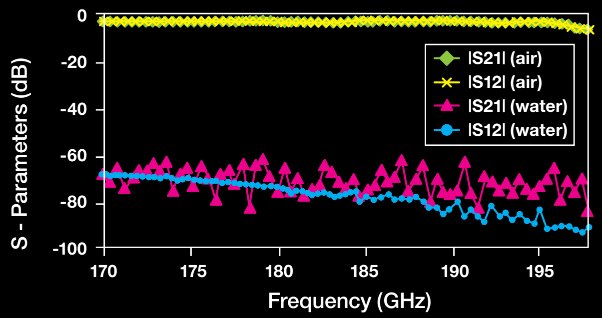
Left: CMBF stereo endoscope assembled inside a commercial camera housing.

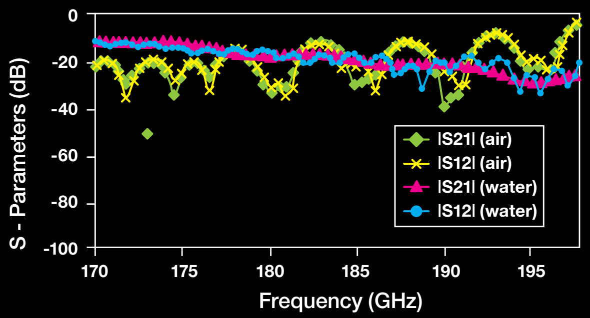


Xenia Amashukeli at work on the µEX instrument, which will enable non-destructive extraction of target compounds.

New Compact Technology Will Enable the Identification and Analysis of Chemical Signatures of Life (Biomarkers) for Future Space Missions

An RF-powered aqueous micro-extractor µEX instrument is a new compact technology that will enable identification, characterization, and analysis of chemical signatures of life — biomarkers — that may be present in planetary samples that would be obtained by the future robotic missions to Mars, NEOs, and other outer- and inner-planetary bodies in our solar system. The basic operational principle of µEX is based on liquid-solid phase separation of target biomarker molecules into the liquid analyte phase from the planetary regolith solid matrix with a high-purity solvent — water that is subjected to RF radiation. Unlike sample-preparation technologies that are based on a pyrolysis method, the µEX instrument will enable non-destructive extraction of target compounds and is expected to induce minimal chemical alternation of the original intrinsic chemical properties of the target compounds. µEX enables extractions by producing change in the chemical solvent properties of water through manipulation of its physical properties, such as the dielectric constant that changes as a function of RF frequency and power.





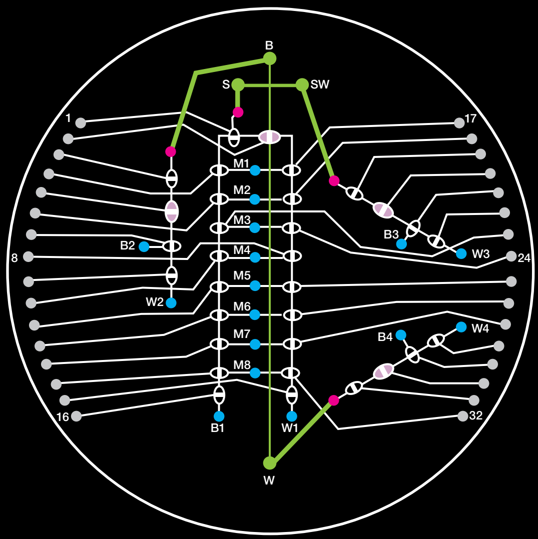
Above: The µEX waveguide block is a two-port RF system, where S11 and S22 are the reflection and S12 and S21 are the transmission parameters. The values of S-parameters as a function of frequency were recorded for the Teflon tubing with and without water. The change in transmission S-parameters with addition of water is approximately -60 dB. The change in the S11 and S22 parameters is less than -10 dB between 178 and 180 GHz. S-parameter data suggest that power losses in the µEX instrument are minimal and that water is very effective at absorbing a 180-GHz signal inside the µEX Teflon extraction channel.

Microfluidics

As planetary science has evolved from the successful observational missions of the 70s, 80s, and 90s, increased emphasis has been placed on the exploration of nearby accessible planets. This has resulted in the development and deployment of new physical, chemical, and geological instruments on robotic platforms. Our group in the MDL is concerned with the development of the next generation of miniaturized “lab-in-a-teacup” systems that can perform chemical analyses without needing to have a human operator present during the process. Such technology is essential to NASA’s search for habitable environments, prebiotic chemical syntheses, and extraterrestrial life in the solar system.

The addition of two postdoctoral fellows, Dr. Morgan Cable and Dr. Fernanda Mora (pictured), has helped us make great strides in this endeavor.

Microdevice for Automated CE Analysis



Stop Valve
Fluid doesn't flow through the junction unless valve is actuated.

Bus Valve
Fluid can flow through the fluidic bus but cannot pass horizontally unless valve is actuated.

External Fluid Entrance
Drilled reservoir in wafer stack.

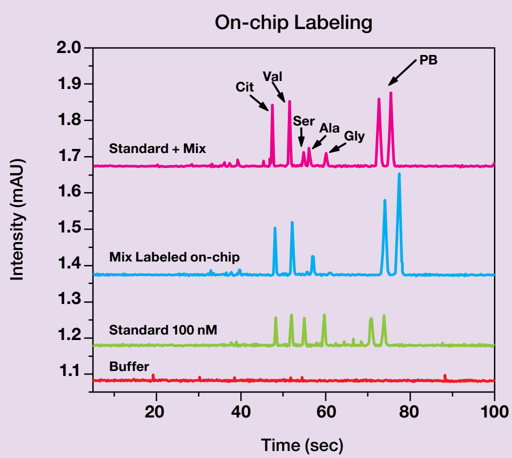
CE Well Entrance
Opening in the membrane that allows fluid to pass down to the CE well.

Left: The layout of a chemistry "circuit" designed for the purpose of performing automated analyses for amino acids. Experiments have been performed in which a sample of amino acids (of a composition not unlike what might be expected on Titan) is placed on the surface of a chip.

MDL Furthers Technology Essential to NASA's Search for Habitable Environments, Prebiotic Chemical Syntheses, and Extraterrestrial Life in the Solar System

Over the past year we have made great strides in this endeavor, largely due to increased interactions with university and industrial partners. The chemical system that we have focused on is Saturn's largest moon, Titan. Radar and infrared measurements from JPL's ongoing Cassini mission have convincingly determined that an active "hydrological" cycle exists on Titan, in which liquid hydrocarbons play the role that water does here on Earth. Hence, in addition to wind and rain on Titan, there currently exist lakes filled with hydrocarbons, which host an exotic and unexplored chemical environment rich in organic chemistry, unlike anything else in the solar system.

We have taken two approaches to the potential future chemical exploration of Titan: the development of an automated lab-on-a-chip system capable of performing all the stages required for the analysis of amino acids, and the development of a miniaturized portable lab-on-a-chip system that can be coupled to a mass spectrometer, in order to do a mass analysis on the large, complex molecular structures expected on Titan. Both of these technology efforts, however, could be utilized here on Earth with effectively no modifications, as part of a handheld system that experimenters could use for the analysis of petroleum products, dirt/soil, water, toxic wastes, or even complex mixtures thereof. Furthermore, these tools could be modified (both in the chip design and the off-chip components) to perform analyses on any sample desired, provided it was possible to dissolve at least some fraction of the sample of interest in liquid.

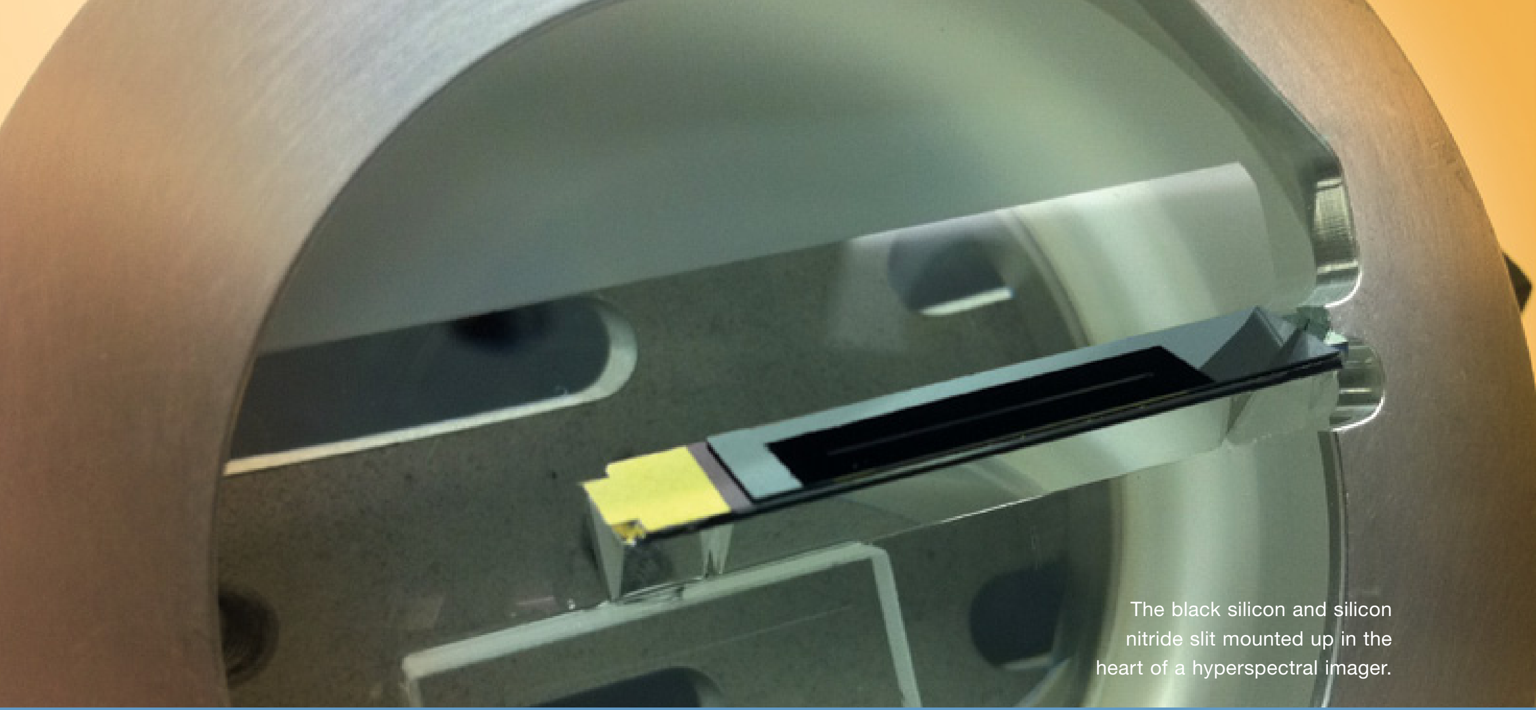


Above: The data are collected near the exit of a microchannel. Each of the peaks that appear in these data traces corresponds to a unique chemical species that can be identified based upon its migration time.

Fabrication Technologies
Unique to the Microdevices Laboratory

Cutting-edge JPL flight instruments have set extreme requirements in precision, mass, and reflectivity that can surpass the ability of traditional fabrication techniques. So scientists and engineers at JPL's MDL are busy developing techniques using tools in the MDL's cleanroom to fabricate these next-generation precision optical components that will bring new capabilites to NASA flight missions and scientific instruments. Take for example, MDL's black silicon and silicon nitride slit, which has been delivered for flight on a hyperspectral imager. It is a superlative example of several unique MDL technologies coming together for a flight component.

A close-up view of a black silicon and silicon nitride slit. The black silicon absorbs almost all the light that does not pass through the slit itself, keeping stray light down to an absolute minimum.



The black silicon and silicon nitride slit mounted up in the heart of a hyperspectral imager.

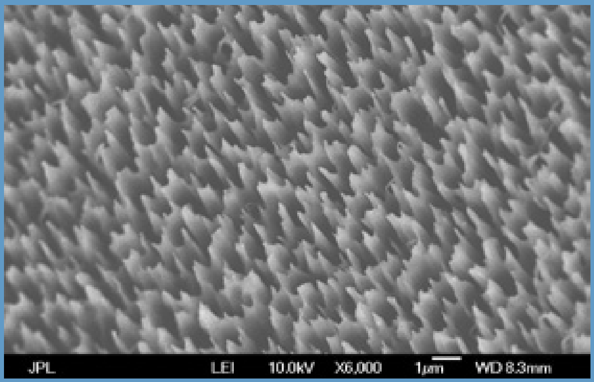
Next-Generation Precision Optical Components Go Micro

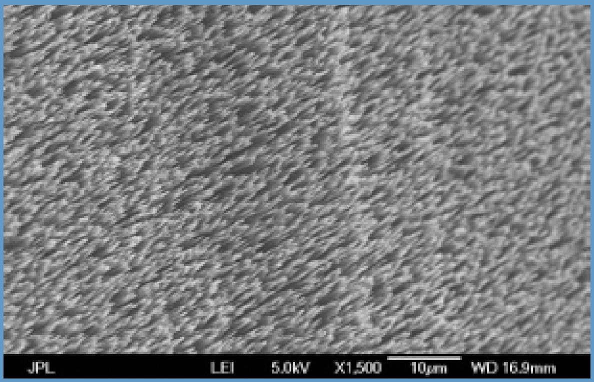
The JPL Silicon Nitride Membrane Slit

Silicon nitride is, in short, a wonder material. It has amazing strength, chemical inertness, radiation resistance, and temperature stability. It is a ceramic material deposited via low-pressure chemical vapor deposition (LPCVD for short) in thin layers on a silicon wafer. Free-standing membranes with an ultra-precise slit are etched through a 1-μm-thick nitride membrane. Using MDL cleanroom tools, it is relatively easy to get 0.25-micron precision over a slit 1.7 cm long.

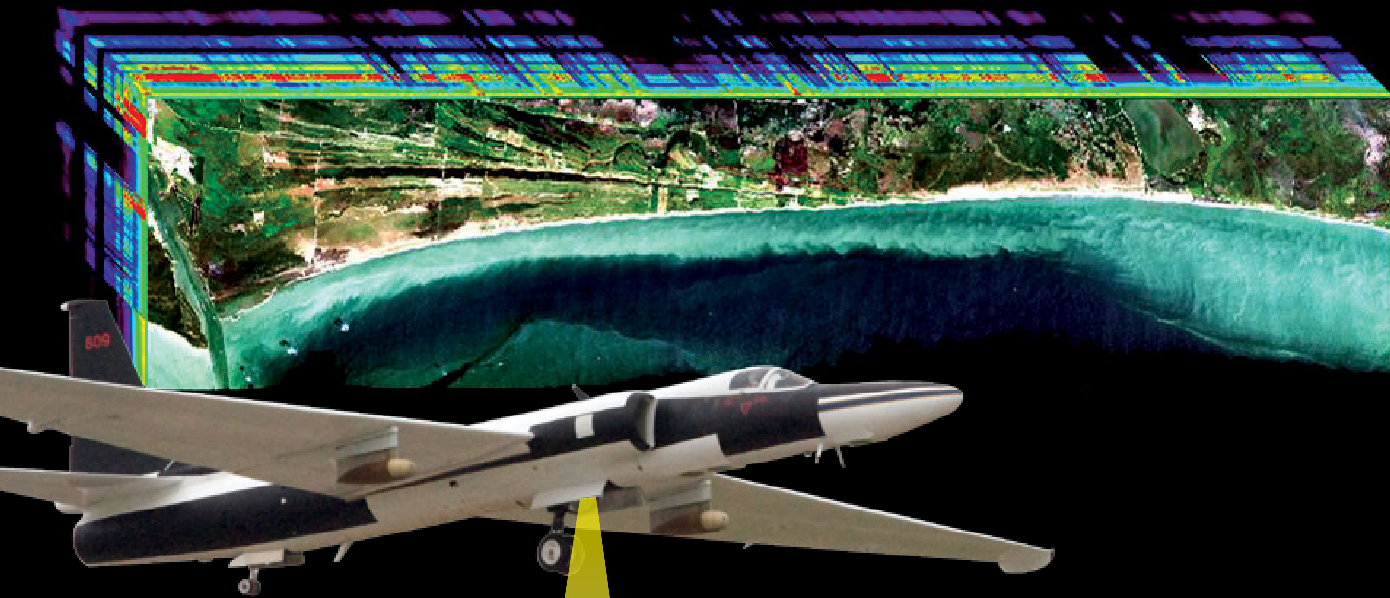
MDL Black Silicon

The JPL silicon nitride slit "selects" the light that goes through the slit for analysis, but "rejects" the light that does not make it through the slit. A major challenge was not letting this rejected light contaminate the sensitive signal the scientists care about. This rejected light has to be eliminated from the system. An MDL invention is a process compatible with the silicon nitride slit, which patterns with extreme accuracy a super-roughened silicon that absorbs almost all light (in excess of 99.9%).





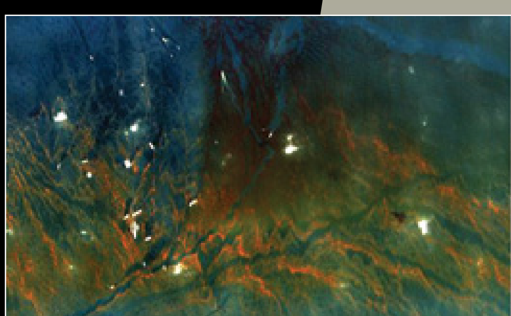
Above: High-resolution SEM images of the highly roughened structure that makes the black silicon black.



At the request of the National Oceanic and Atmospheric Administration, NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) flew in a NASA ER-2 aircraft to extensively map the gulf region affected by the 2010 Deepwater Horizon BP oil rig disaster.

Above: AVIRIS maps like this one over the Louisiana coast will be used to provide a baseline of ecosystems and habitats that can be compared with data from future AVIRIS flights to assess the impacts of the oil spill.

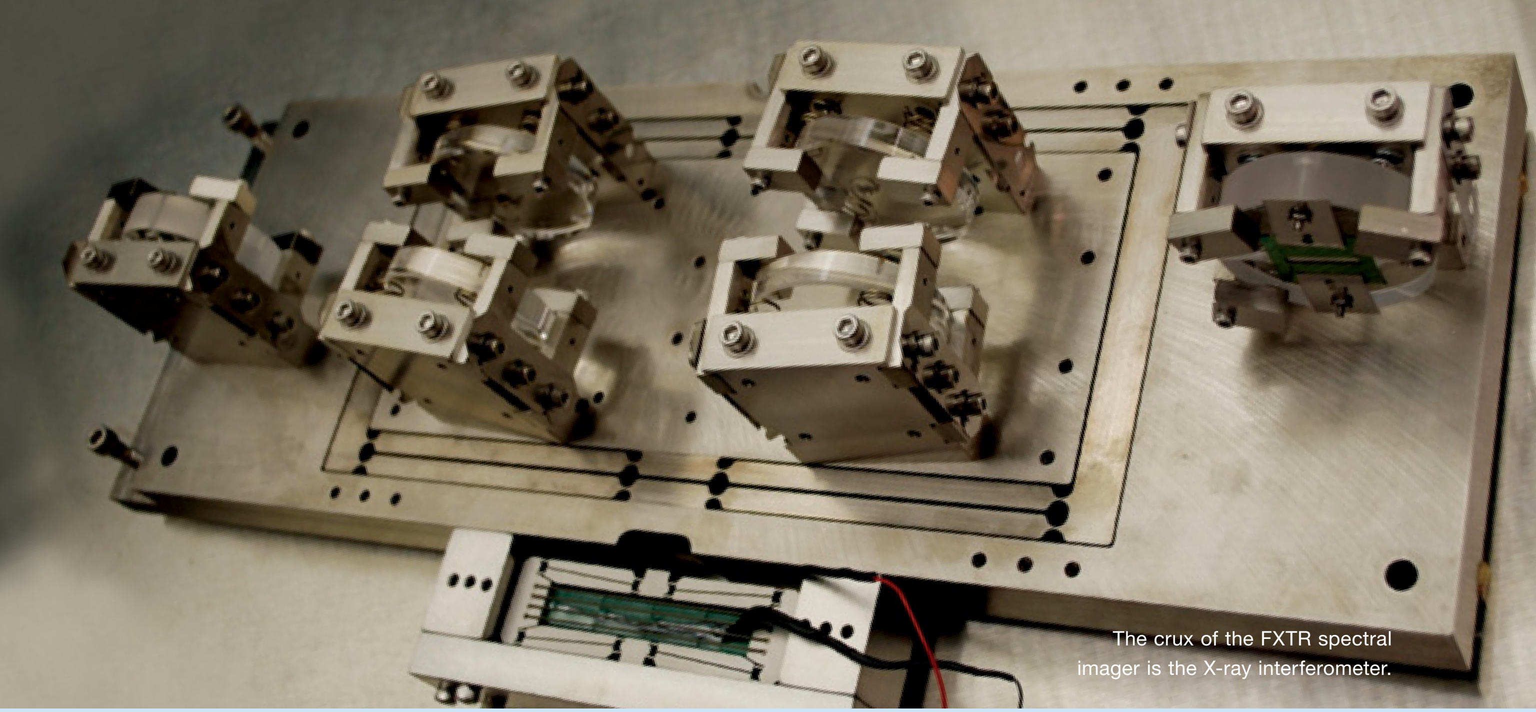
Below: In this AVRIS image, crude oil on the surface appears orange to brown.



"Spectral Images" for Chemical Analyses on Both Earth and Spacebound Flights

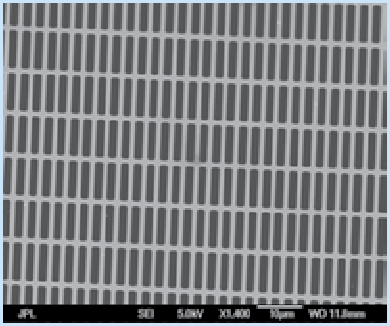
JPL is a world-class leader in the development of cutting-edge flight instruments that both look out into space and down onto Earth. Among the classes of optical instruments JPL is developing are what is known as hyperspectral imagers. These instruments look down from above to take high-resolution spectral images. By this, we mean that each pixel on each high-resolution image conveys spectral information that can be analyzed to determine the chemistry at that pixel. MDL has been leading development of various microfabricated parts for these hyperspectral imagers for years, creating critical parts such as the hemispherical blazed grating and open air slits. The air slits made in MDL are arguably the world's highest quality open air slits. These slits help diffract out the light into their spectral components. Recently, a JPL imaging spectrometer (AVIRIS) was flown over the Gulf of Mexico oil spill to gather data on the oil spill (left).

To increase chemical sensitivity, both spectral resolution and the signal-to-noise ratio must be optimized. To facilitate this, a brand-new class of materials has been developed for insertion into the JPL slits – black silicon. Black silicon is normal silicon that has been etched in such a way that it creates an ultra-rough surface that absorbs almost all light. While the technology is in its infancy, it has already been delivered for a flight instrument, the PRISM hyperspectral imager with more missions and applications in the queue.



The crux of the FXTR spectral imager is the X-ray interferometer.

Fourier Transform X-ray (FTXR) Spectral Imager



Above: SEM image of the beam splitter.

A novel miniature spectral imager in the soft X-ray region is being developed. The imager adapts FT techniques used in the IR to X-ray spectral region, with correspondingly increased spectral and spatial resolution. The crux of the imager is an X-ray interferometer, the enabling component is a beam-splitting mirror. We have prepared beam splitters based on JPL-pioneered perforated membrane technology. The fabricated beam splitters meet specification on surface flatness in the VUV spectral region — something that has eluded other researchers for years — and incorporated them into a proof-of-concept Mach-Zehnder-type interferometer that has also been assembled at JPL. Applications for NASA include determination of bonding structure of chemically relevant elements in minerals; applications for DOE and NHI include fingerprinting molecular structures.

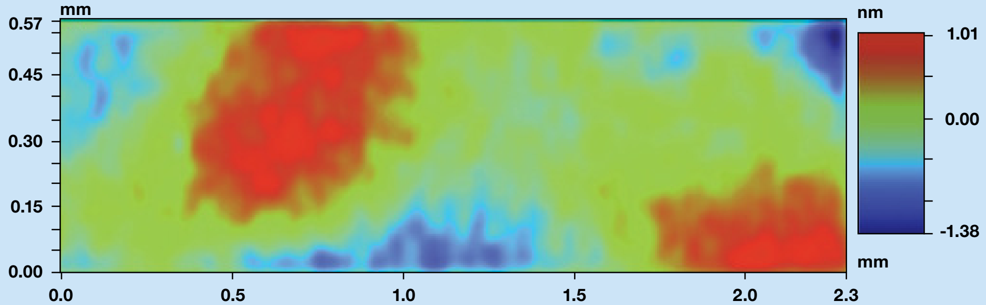
Surface Flatness Data

Surface Statistics
Ra: 0.33 nm
Rq: 0.41 nm
Rz: 1.87 nm
Rt: 2.39 nm

Set-up Parameters
Size: 317 x 80
Sampling: 7.26 mm

Processed Options
Terms removed: None
Filtering: DLP (10/mm)

Mag: 1.4 X Mode: PSI



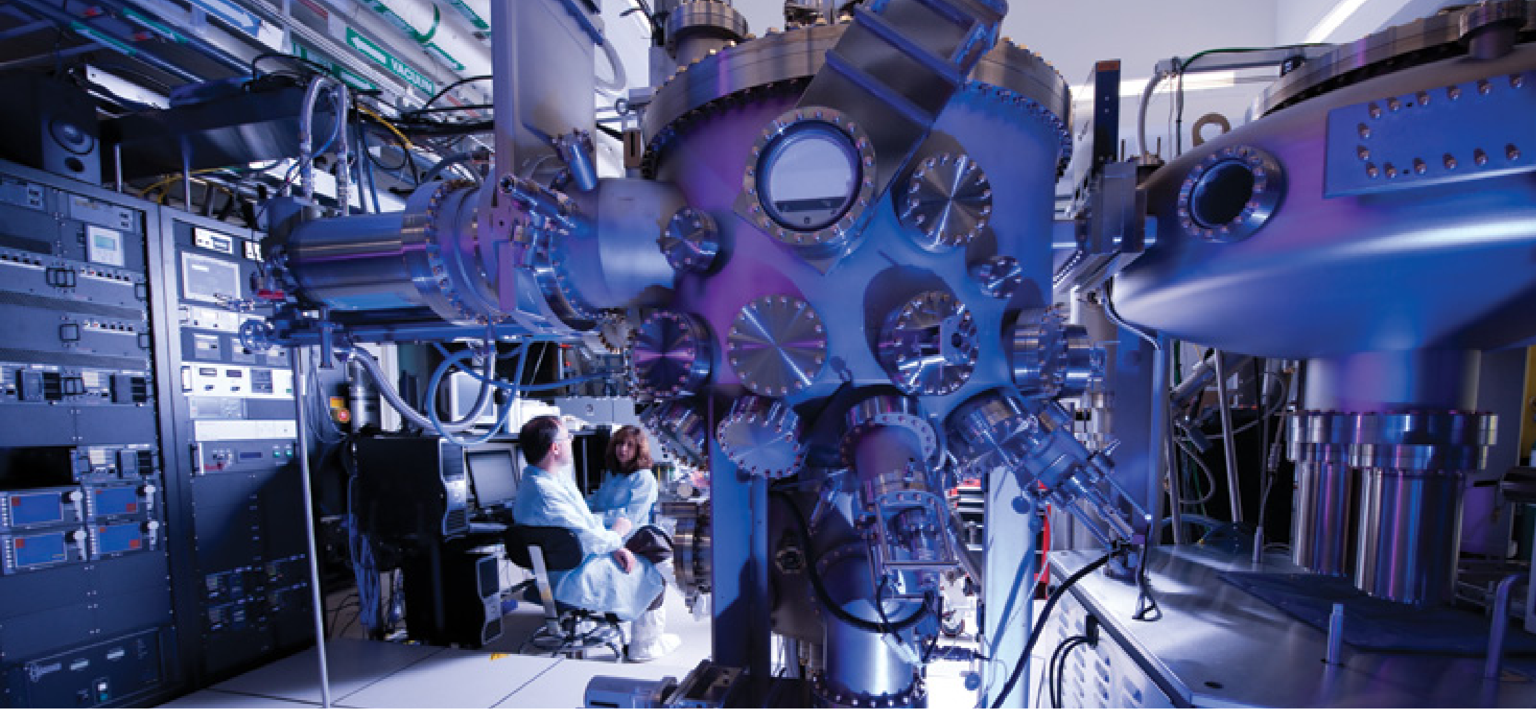
Appendix A — MDL Equipment Complement

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
- Plasma-Enhanced Chemical Vapor Depostion (PECVD) Systems for Doped and Undoped Amorphous Silicon
- 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
- Low-Pressure Chemical Vapor Deposition (LPCVD) (Tystars) with 6 Tubes for
  - Low-Stress Silicon Nitride (2)
  - Low-Temperature Oxide – Silicon Dioxide
  - Doped and Undoped Polysilicon
  - Wet Pyrogenic Oxidation
  - Steam Oxidation
- Carbon Nanotube Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  - Veeco GEN200 (8-inch) Si MBE for UV CCD Delta Doping (Silicon)
  - Veeco Epi GEN III MBE (Antimonide Materials)
  - Riber MBE for UV CCD Delta Doping (Silicon)
  - Riber Device MBE (GaAs)
- Thomas Swann Metallo-Organic Chemical Vapor Deposition (MOCVD) System

LITHOGRAPHIC PATTERNING

- Electron-Beam (E-beam) Lithography: JEOL JBX9300FS E-beam lithography system with a 4-nm spot size, 100,000-volt acceleration voltage, ability to handle wafers up to 12 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 3 mm of sag
- GCA Mann Wafer Stepper with custom stage allowing different sizes and thicknesses of wafers (0.7 μm resolution)
- Canon EX3 Stepper with EX4 Optics (0.25-μm resolution)
- Contact Aligners:
  - Karl Suss MJB3
  - Karl Suss MJB3 with backside IR
  - Suss MA-6 (UV300)
  - Suss BA-6 (UV400) with jigging supporting Suss bonder
- Wafer Track/Resist/Developer Dispense Systems:
  - Suss Gamma 4 Module Cluster System
  - Site Services Spin Developer System
- Yield Engineering System (YES) Reversal Oven
- Ovens, Hotplates, and Manual Spinners



DRY ETCHING

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

FLUORINE-BASED PLASMA ETCHING SYSTEMS

- STS Deep Trench Reactive Ion Etcher (DRIE) with SOI Upgrade
- Unaxis Shuttleline Load-Locked Fluorine ICP RIE
- Plasmaster RME-1200 Fluorine RIE
- Plasma Tech Fluorine RIE
- STJ RIE for Superconductors
- Custom XeF2 etcher

CHLORINE-BASED PLASMA ETCHING SYSTEMS

- Unaxis Shuttleline Load-Locked Chlorine ICP RIE
- Plasmaster RME-1200 Chlorine RIE
- ECR 770 Chlorine RIE
- Oxford Inductively Coupled Plasma (ICP) Chlorine RIE

WET ETCHING & SAMPLE PREPARATION

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (7)
- Rinser/Dryers for Masks and Wafers
- Chemical Hoods (7)
- Acid Wet Processing Benches (8)
- Critical Point Dryer
- Rapid Thermal Processors/Contact Alloyers (2)
- Polishing and Planarization Stations (5)
- Strasbaugh 6EC Chemical Mechanical Polisher

PACKAGING

- SET FC-300 Flip-Chip Bump Bonder
- Karl Suss Wafer Bonder
- Electronic Visions Wafer Bonder
- Research Devices Bump Bonder (High Pressure)
- 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

CHARACTERIZATION

- Profilometers (2)
- Film Stress Measuring System
- Leitz Interferometer
- Multispectral Ellipsometer
- Atomic Force Microscope
- KLA-Tencor Surfscan 6220 Wafer Particle Monitor
- JEOL JSM-6700 Field Emission SEM with EDX
- Nikon Inspection Microscope with Image Capture
- Confocal Microscopes
- Electrical Probe Stations with Parameter Analyzers (3)
- Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectroscopy
- X-ray Diffraction System
- XPS with Thermal Stage
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)

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