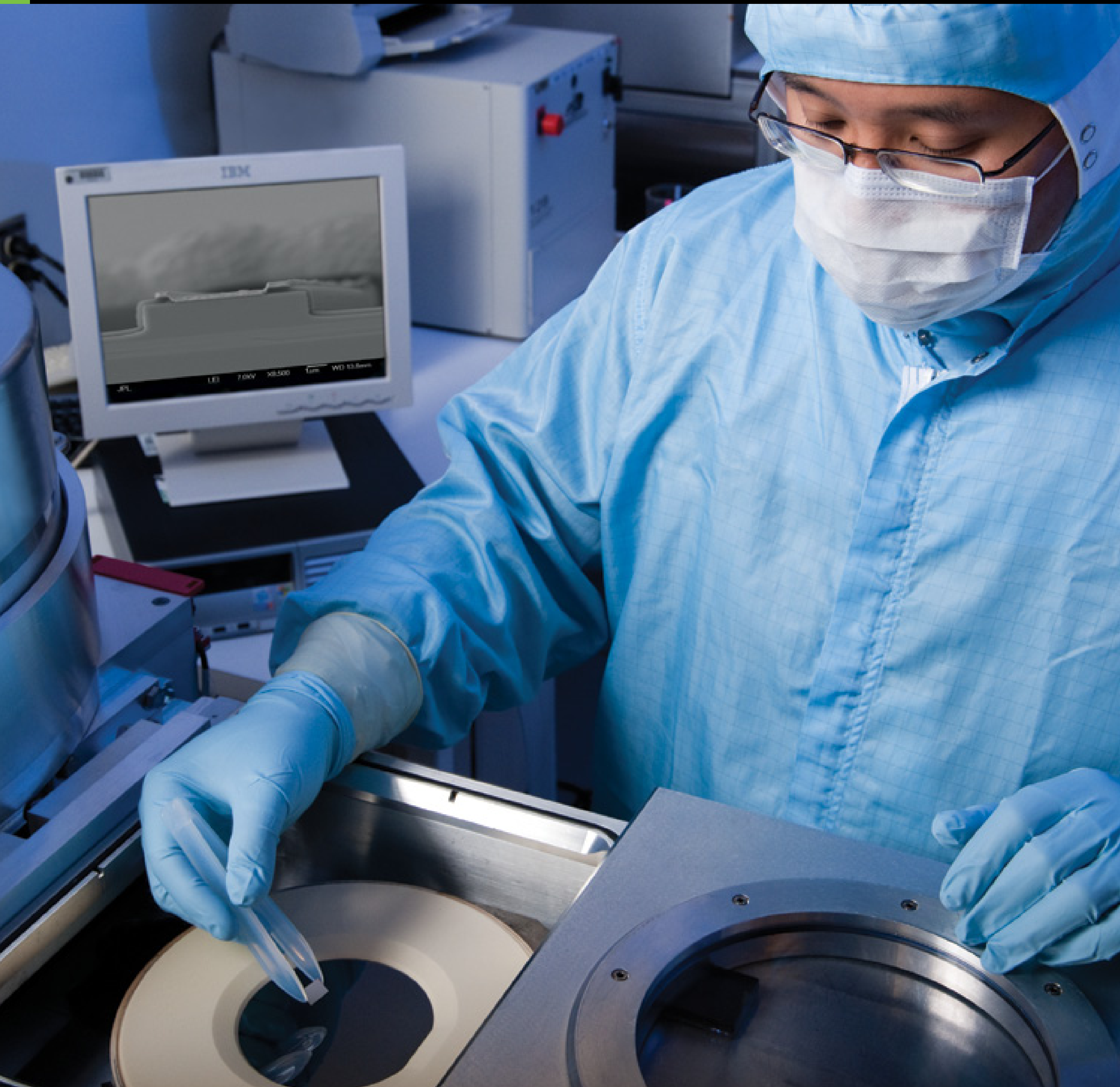
National Aeronautics and Space Administration

jet propulsion laboratory

microdevices laboratory

09

annual report



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

MDL is a prime example of JPL's dedicated efforts to create and deliver high-risk, high-payoff technologies for NASA's future planetary, astrophysics, and Earth science missions.

director's letter

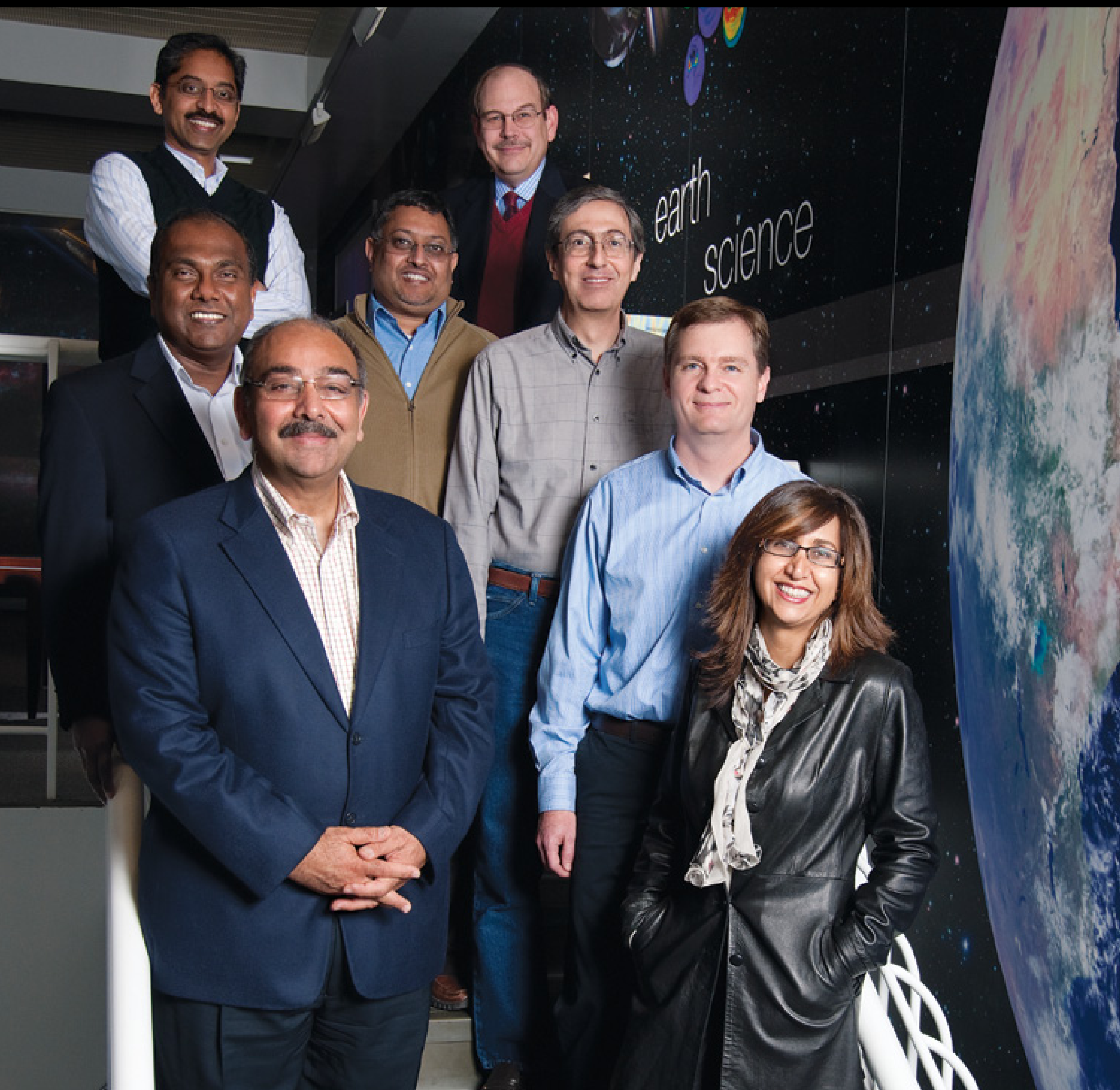
Our lives are punctuated by major events that usually represent beginnings or endings — birthdays, graduations, and weddings are just a few examples. As scientists, we are also fascinated by such events. What was the early Universe like, and what will eventually happen to it in the distant future as it keeps on expanding? How do galaxies, stars, and planets form? How did life originate and evolve on Earth? Did life manage to get started on another body in our solar system, or somewhere else in the Universe? These are a few examples of the big questions that motivate our work at the Microdevices Laboratory. Of course, the Microdevices Laboratory (MDL) has its own beginning, which can be traced back to 1982 when Dr. Lew Allen became JPL's Director. Indeed, the MDL was conceived, constructed, and put into operation under Allen's leadership. Sadly, endings often follow beginnings — Dr. Allen passed away on January 4, 2010, at the age of 84.

May 2009 saw JPL's WFPC-2 instrument return to Earth from the Hubble Space Telescope, marking an end to its spectacularly successful scientific career. Fortunately, in this case a beginning is following an ending. The difficulties encountered in producing ultraviolet-sensitive CCD detector arrays for WFPC and WFPC-2 spurred the invention of the delta-doping technique by JPL scientists Frank and Paula Grunthaner. With the 2009 installation of a new high-capacity molecular beam epitaxy system, the MDL is now poised to enable a new generation of missions and instruments, such as a spectroscopic version of NASA/JPL's highly successful GALEX ultraviolet astronomy mission.

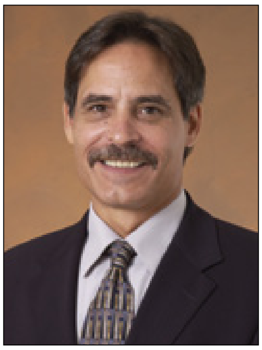
May 2009 also saw two beginnings with the successful launch of the Herschel and Planck spacecraft. Equipped with very sensitive, MDL-produced detectors, these spacecraft are now executing science operations, studying the Cosmic Microwave Background at millimeter wavelengths (Planck) and the formation of galaxies and stars at submillimeter and far-infrared wavelengths (Herschel). In my photograph on the left, taken in the MDL lobby, an image of the April 27, 2000, cover of the prestigious scientific journal Nature is visible. The subtitle reads "Background to a flat universe," neatly summarizing the spectacular, epoch-defining scientific result achieved with the BOOMERANG balloon experiment, using MDL detectors that served as prototypes for Herschel and Planck. Indeed, Lew Allen's Microdevices Laboratory was a significant factor in attracting Andrew Lange to the Caltech faculty in 1994, and his student (now Senior Research Scientist) Jamie Bock to JPL, for it was MDL that offered them the facilities that they needed for detector development. But an ending has come: on January 22, 2010, the news of Andrew Lange's passing at age 52 left us shocked and stunned. I knew Andrew well and will miss him deeply, and I will always remember and be very grateful for the amazing example that he set for us at MDL.

Jonas Zmuidzinas
Director, JPL Microdevices Laboratory

As you will read in this Annual Report, it has been another productive year for the MDL. The range of development spans that of the earliest concept to technologies that are fine-tuned for flight implementation.



division manager's statement



We have completed our 20th year of operation at MDL and the work today is just as exciting as in our inaugural year. This year we saw the fruition of several technologies developed in the Microdevices Laboratory. Thermopile detectors enabled the Diviner Lunar Radiometer Experiment on the Lunar Reconnaissance Orbiter, spider-web bolometers enabled the development of the Spectral and Photometric Imaging Receiver on the Herschel mission and the High-Frequency Instrument on the Planck mission, and Schottky and SIS devices enabled the Hetrodyne Instrument for the Far-Infrared (HIFI) on the Herschel mission. Each of these instruments are returning data and producing scientific results that could only be imagined a few short years ago. It is this kind of technology development and infusion that reinforces the MDL at JPL.

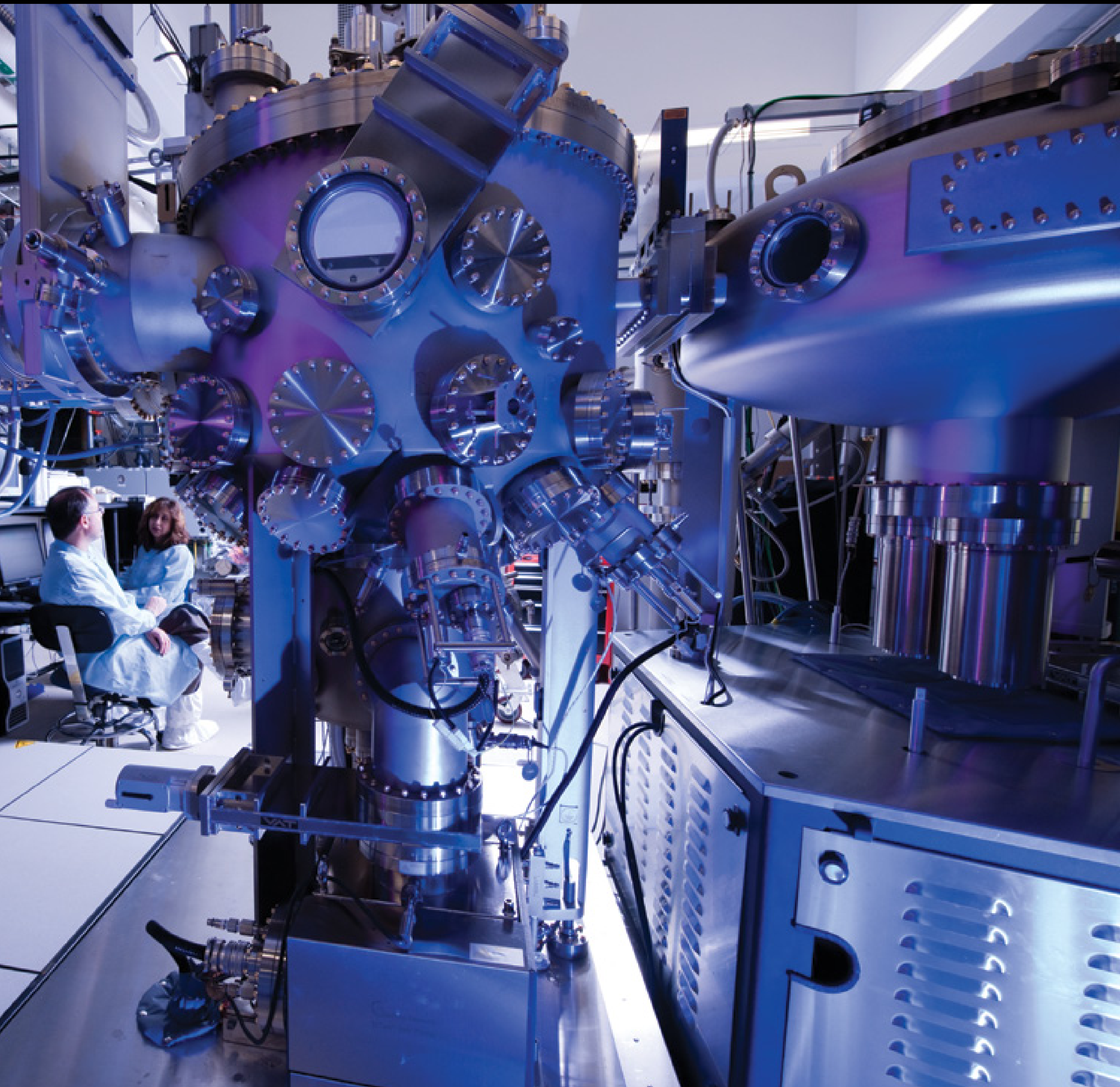
We have continued to work with the MDL director, Professor Jonas Zmuidzinas, defining new investments for the coming years. We are completing the installation and validation of the high-throughput silicon Molecular Beam Epitaxy (MBE) machine, purchased last year. This year we have focused our investments in two areas: a bump bonder for hybridizing large-format detectors, and a high-vacuum system for deposition of high-purity exotic materials for thermopile detectors. We expect these investments to strengthen and expand our capabilities in infrared and millimeter range detectors and provide new observational capabilities to future NASA scientific instruments.

As you will read in this Annual Report, it has been another productive year for the MDL. The range of development spans that of the earliest concept to technologies that are fine-tuned for flight implementation. We are proud of the tradition of enabling new scientific instruments through the use of our technologies, whether in space flight, airborne applications, or in basic research. 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

Opposite page: MDL's leadership team. Pictured (top to bottom, left to right): Harish Manohara, James Lamb, Sarath Gunapala, Imran Mehdi, Richard Vasquez, Deputy Director Siamak Forouhar, Daniel Wilson, and Shouleh Nikzad.

Open to all JPL personnel, the Microdevices Laboratory functions as a flexible facility, allowing research, development, and small-scale production of a very broad range of devices.



infrastructure, operations, and capabilities

overview

Microdevice fabrication requires sophisticated equipment for the deposition, etching, and patterning of device layers, and must generally be done in a very clean environment to avoid defects and contamination. As a result, it is highly desirable to co-locate such activities, to allow expensive equipment to be shared, and to spread the maintenance burden over a larger base of activity.

While industrial “fabs” are usually designed for mass production of devices using a standard process, the MDL is much more flexible, allowing research, development, and small-scale production of a very broad range of devices. The MDL functions as a multi-user and shared equipment facility that is open to all JPL personnel; MDL access for users from outside institutions can also be arranged. The MDL Central Processing Group led by James Lamb is responsible for operational safety, facility maintenance, and installation and maintenance of shared-use equipment. This group is supported by MDL users through access fees and special equipment usage fees, and is also directly supported by JPL institutional funds.

The heart of MDL is a 13,000-square-foot cleanroom that is used by over 70 research scientists. The MDL cleanroom is divided into various zones according to cleanliness standards, ranging from class 100,000 (ISO 8) for the rooms housing epitaxial deposition systems, to class 10 (ISO 4) for the lithography area. The MDL contains over 130 individual pieces of processing equipment, including systems for UV contact and projection lithography, electron-beam lithography, materials growth and deposition, wet and dry etching, thermal processing, and optical, structural, and electronic characterization. Much of the equipment is available to all MDL users on a shared basis; however, some equipment is dedicated to individual groups.

equipment investments and upgrades

Continuous investment in MDL’s processing equipment is essential. The equipment for micro- and nano-fabrication continues to develop at a very rapid pace, driven primarily by the semiconductor industry, and the timescale for obsolescence is short. As a result, in some cases MDL is able to acquire previous-generation production equipment at a substantial discount; a good example is MDL’s primary photolithography tool, the Canon EX3 deep-UV

infrastructure, operations, and capabilities year-in-review

projection lithography system capable of 0.25 µm resolution. However, because the MDL focuses on unique devices for space applications rather than the mass production of commodity chips, production equipment is not always suitable — MDL equipment is often smaller in scale, and may be custom built for specific requirements. The dedicated ultra-high-vacuum (UHV) sputtering systems used to deposit superconducting films are examples of the latter category. Additional detail on MDL's equipment complement may be found on page 58.

2009 highlights

In 2009, the major operations highlight was the 50% reduction in fees per user from \$50K/yr to \$25K/yr that was instituted that year. Enabled by both a management reorganization in 2008, and a fundamental change in the way fees were collected that reduced overhead costs, the fee reduction was declared a success when an increased user base, a balanced budget, and resources for some internal infrastructure improvements resulted. The access fees per user will remain unchanged for 2010.

MDL continued to develop its capabilities for producing large detector arrays and the processing of 150-mm (6-inch) diameter wafers through the installation of equipment purchased in 2008, as well as new investments. Enhanced capabilities purchased in 2008 and installed in 2009 include:

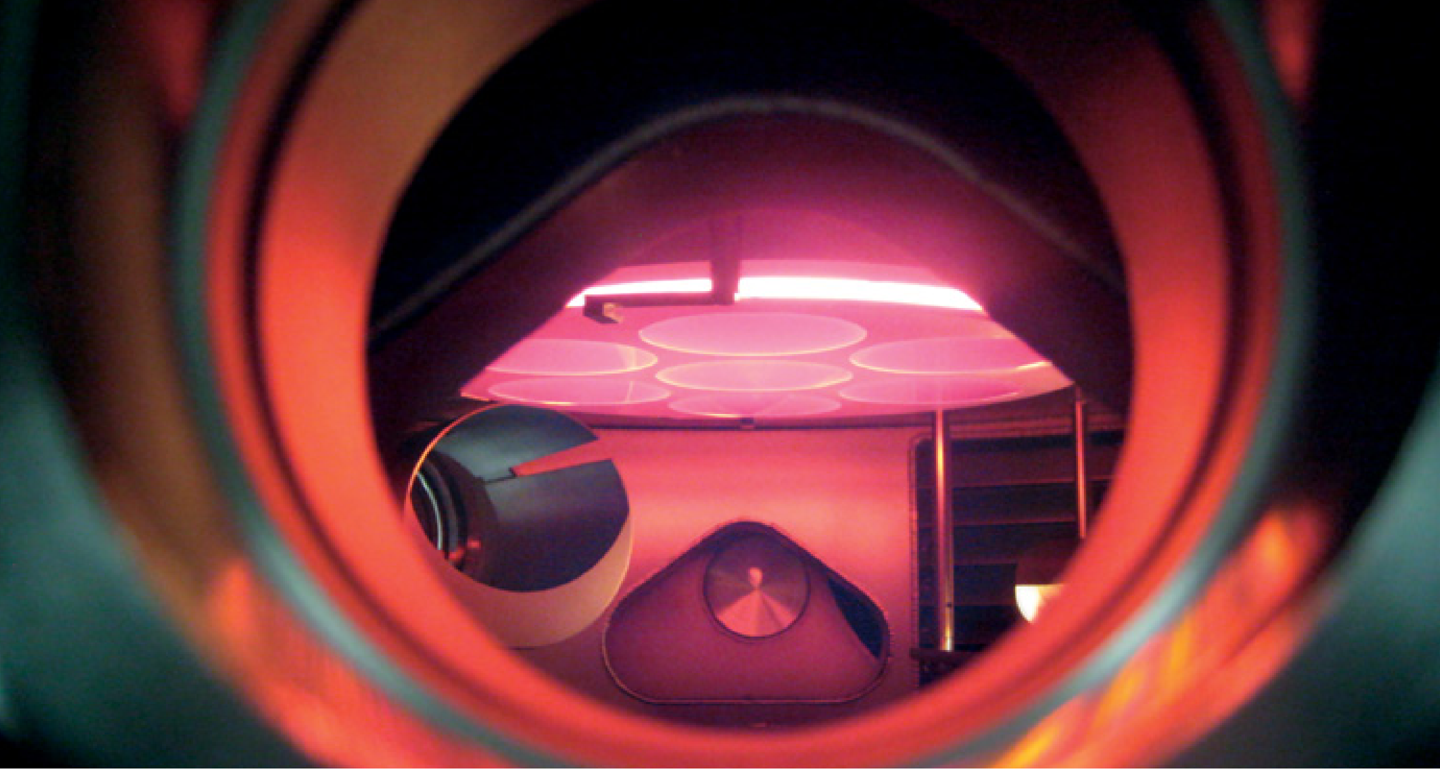
- Veeco GEN200 (8-Inch) silicon molecular beam epitaxy (MBE) system. The system provides a means of producing delta-doped enhanced charge-coupled device (CCD) and CMOS imagers of a substantial size at the wafer level. Its installation required rerouting of facilities and raising the ceiling above the unit.

New Process Cooling Water system for MDL cleanrooms with increased capacity and control for instrument cooling needs.

- silicon on insulator (SOI) and computer software upgrade for the existing STS Deep-trench Reactive Ion Etcher (DRIE). This capability prevents charging at the bottom of trench etches, eliminating notching at the base of the trenches and enhancing the precision of the side wall etches in general.

New capabilities purchased and installed in 2009 include:

- enhanced radical atomic layer deposition (ALD) upgrade for the Oxford Plasmalab 80 OpAL ALD system. This upgrade expands the high-energy processes and particle energetics for this precision CVD system, expanding the range of materials and coating types possible for this capability.



In October, energy management was enhanced by reducing air flows in off-hours through the use of variable-speed motors with particle monitoring controls for MDL's 6 Air Handlers and 32 Recirculating Units (RCUs).

- KLA-Tencor Surfscan 6220 wafer particle monitor. This system has been configured to exclusively handle the 50-mm, 75-mm, and 100-mm diameter wafers that come out of the antimony MBE for QWIP applications.
- Olympus LEXT microscope with vibration isolation table and workstation for QWIP bump bonding applications.
- Suss Probe station and software upgrade to allow enhanced throughput and probe card testing.

In addition to the equipment investments, numerous facility upgrades were implemented in 2009. In January, long-life replacement ULPA filters for the MDL cleanrooms were installed, which should last until the 2019 to 2023 timeframe. In March, a new Process Cooling Water system was brought on line, increasing capacity and control for instrument cooling needs within the facility. In June, a new replacement ProX4 Incipient Fire Detection system was brought on line. It utilizes cloud chambers to nucleate water around and optically detect submicron particles generated by precursor fire events. In October, energy management was enhanced by reducing air flows in off-hours through the use of variable-speed motors with particle monitoring controls for MDL's 6 Air Handlers and 32 Recirculating Units (RCUs). Humidity control and oversight was also improved through the installation of new hot water and chilled water feeds to the building and the installation of an on-line digital humidity monitoring system that can be accessed by users through the MDL internal website.

Oxford Plasmalab 80 OpAL atomic layer deposition (ALD) system with enhanced radical upgrade.

Unique optical components fabricated by electron-beam lithography at the Microdevices Laboratory enable JPL to develop high-performance instruments for NASA and other customers.

optical components

The Microdevices Laboratory develops and delivers unique optical components fabricated by electron-beam lithography to support JPL's mission. Our convex and concave diffraction gratings enable JPL's imaging spectrometers to achieve unmatched spectral efficiency and spatial uniformity in the wavelength range from 350 nm to 12 microns. In addition to providing gratings and slits for flight instruments, we engage in research to develop novel optical components, instruments, and fabrication techniques. This year we developed processes for fabricating larger optics as well as for transfer etching our e-beam fabricated analog-relief surface profiles into silicon, zinc selenide, and gallium antimonide to enable infrared applications.

diffraction gratings

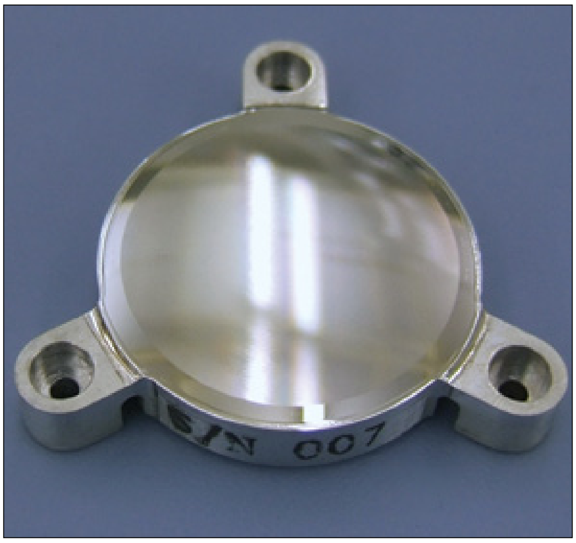
The Moon Mineralogy Mapper (M3) imaging spectrometer successfully completed its mission aboard India's Chandrayaan-1 spacecraft. M3 utilized an MDL designed and fabricated shaped-groove convex diffraction grating to disperse wavelengths from 430 nm to 3000 nm with efficiency tailored to flatten the signal-to-noise ratio of the instrument. Recently the M3 science team reported the discovery of significant amounts of water on the lunar surface as well as accurate mapping of many minerals.

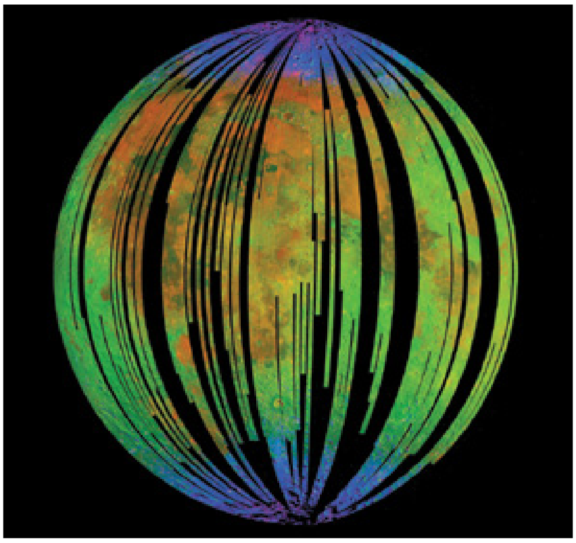
We successfully fabricated a pathfinder triple-blaze convex grating in preparation for three next-generation airborne imaging spectrometers. The grating disperses wavelengths from 350 nm to 2500 nm with a spectral efficiency function that is controlled by the blaze wavelengths and area fractions.

An automated experimental setup was developed to measure the efficiency of convex gratings. The grating is mounted in an Offner optical configuration to uniformly illuminate the grating at the desired angle of incidence. The setup was used to measure the efficiency of the triple-blaze pathfinder grating and the result closely matched that predicted by simulation of atomic force microscope measured groove profiles.

Imaging spectrometers based on the Dyson configuration are even more compact than Offner designs, but they require concave gratings. We have

optical components year-in-review





Left: MDL's e-beam fabricated convex grating used in the Moon Mineralogy Mapper (M3). **Right:** A three-color mosaic derived from the M3 near-infrared spectrometer. Orange and pink colors illustrate the distribution of iron-bearing minerals. Green represents the surface brightness at 2.4 micrometers. Blue indicates the presence of small amounts of surficial OH and H_2O that are most prominent at these viewing geometries at cooler, higher latitudes.

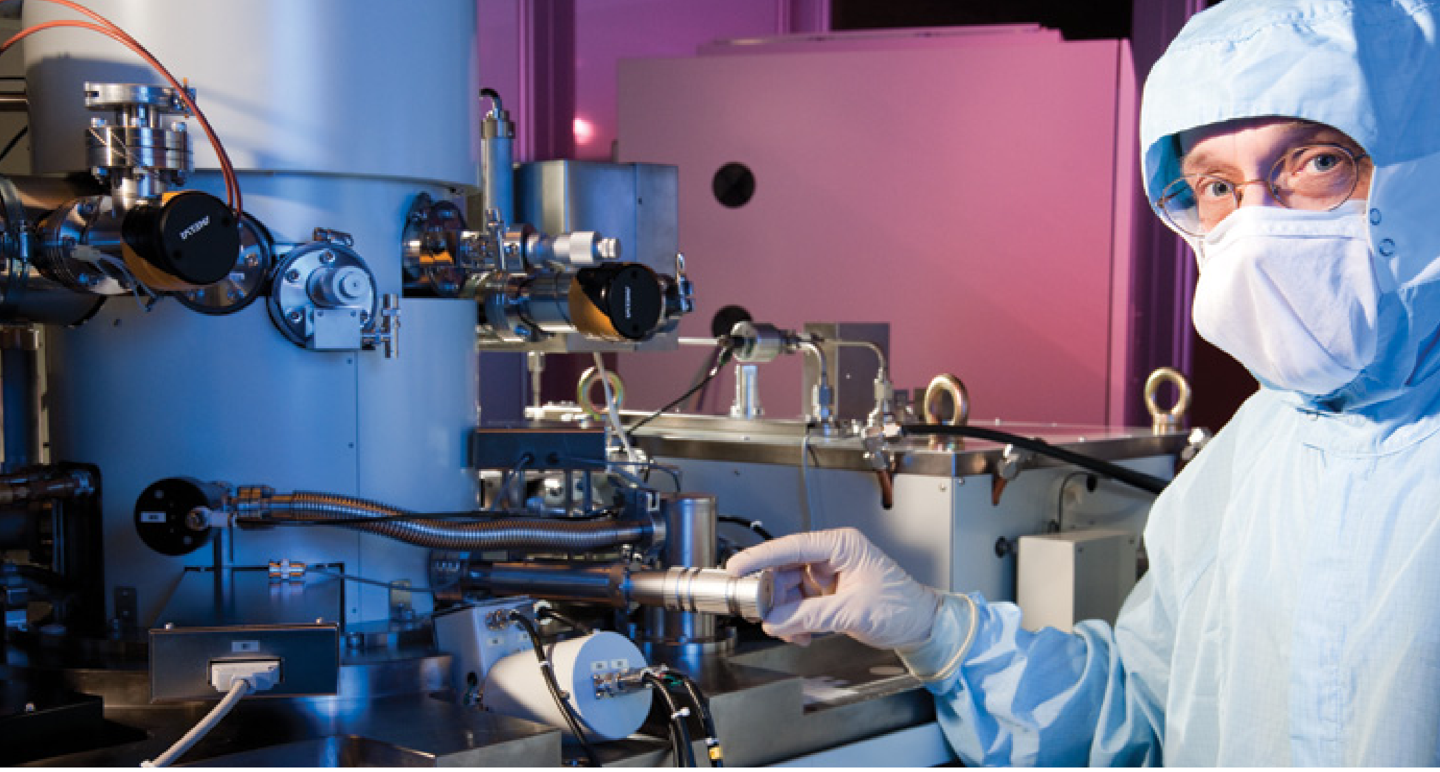
fabricated high-efficiency concave gratings for mid-wave infrared (3 to 5 µm) and long-wave infrared (8 to 12 µm) operation for the Quantum Well Earth Science Testbed (QWEST).

diffractive and subwavelength optics

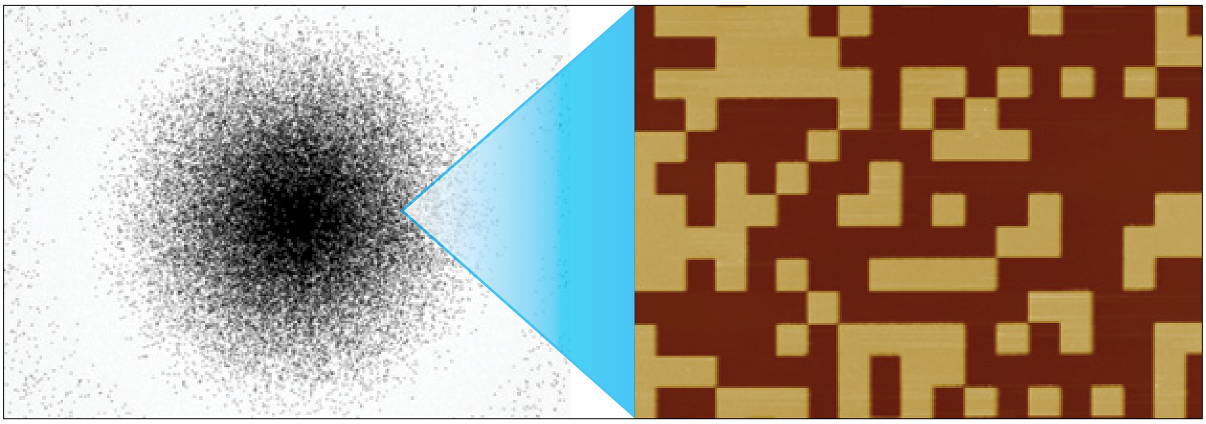
MDL has been selected to fabricate the flight occulting masks for the James Webb Space Telescope (JWST) Near-Infrared Camera (NIRCam) coronagraph. The occulters are binary half-tone patterns composed of near-wavelength-size holes and islands of thick aluminum, patterned by electron-beam lithography followed by plasma etching. The half-tone patterns realize carefully designed apodizing mask functions that block the 1 to 5 µm wavelength starlight focused onto the occulter. The remaining light that passes through the NIRCam coronagraph is reimaged to enable detection and characterization of orbiting exoplanets.

Polarization optical components can be realized by fabricating subwavelength gratings in appropriate materials. This year we improved our process for fabricating patterned wire-grid polarizers, achieving high contrast (greater than 200:1) and high transmission (greater than 80%). We also developed a process for patterning and etching subwavelength grating wave retarders in zinc selenide.

In collaboration with Measurement Science Enterprise, we continue to design and fabricate diffractive optical



MDL has been selected to fabricate the occulting masks for the James Webb Space Telescope (JWST) Near-Infrared Camera (NIRCam) coronagraph. The masks will block the light from a target star to enable detection and characterization of orbiting exoplanets.



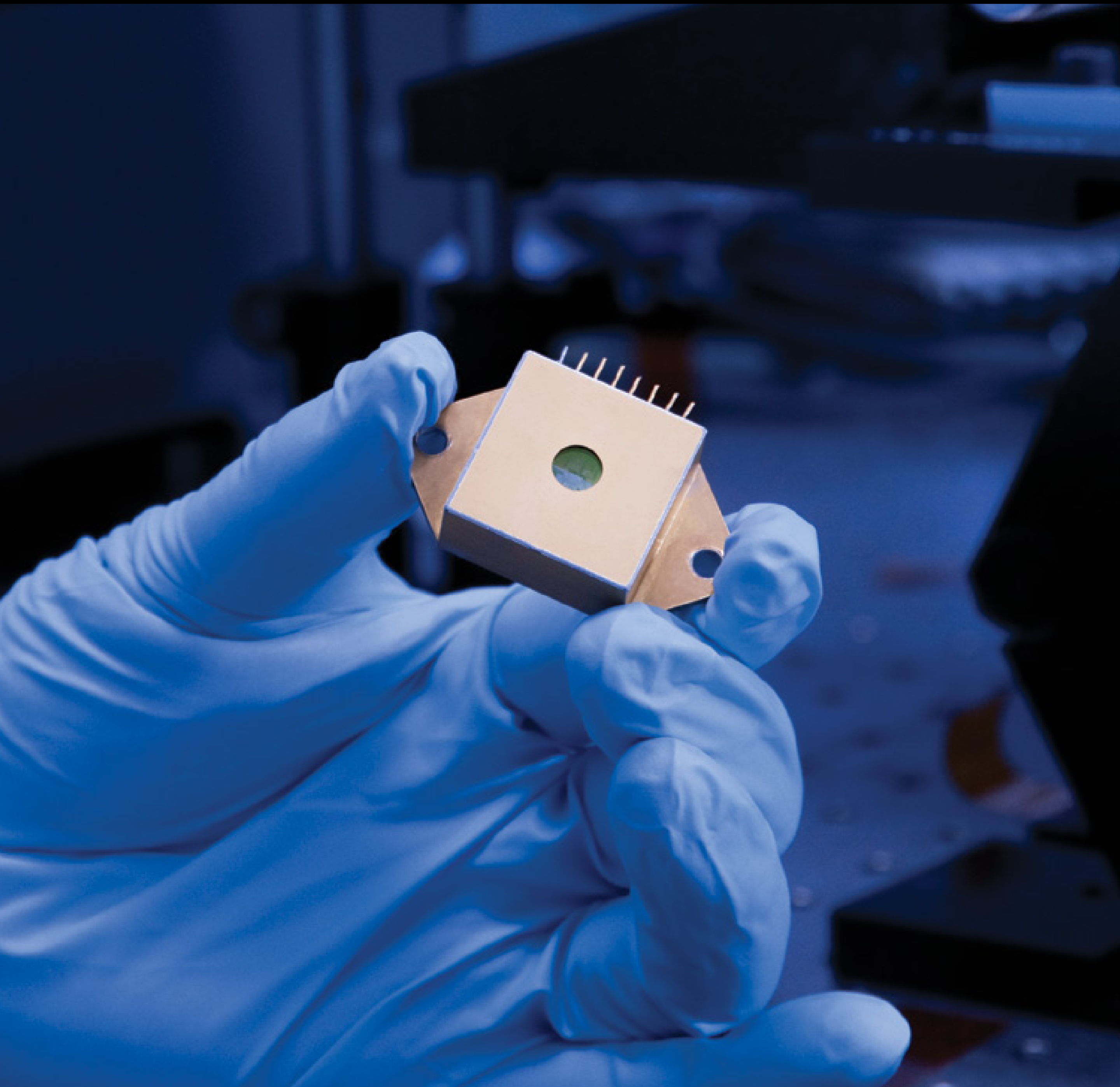
Transmission photograph and atomic force microscope scan of a half-tone occulting mask composed of near-wavelength-sized e-beam fabricated aluminum squares. The granularity is smoothed out when integrated over the image of the star.

elements (DOEs) for non-invasive fluid flow sensors that measure velocity and shear stress. The DOEs produce structured light patterns in the fluid, and particles scatter light to a detector allowing determination of flow parameters.

snapshot imaging spectrometers

Traditional imaging spectrometers require scanning to acquire spectra from a two-dimensional scene. We are developing imaging spectrometers such as the computed-tomography imaging spectrometer (CTIS) and its variants that capture spectral information from a 2D scene in a single snapshot. These systems utilize JPL designed and e-beam fabricated 2D computer-generated hologram gratings on flat (transmissive) and convex (reflective) substrates in various spectrometer optical configurations. Our latest reflective Offner CTIS captures a 2D scene's near-infrared spectra (0.9 to 1.5 μm) simultaneously with a co-registered mid-wave infrared (3 to 5 μm) grayscale image.

NASA has a particular need for tunable infrared lasers, which are used for in situ high resolution spectroscopy in which trace molecules in the atmosphere of Earth or another planet may be precisely identified and studied by measuring their infrared absorption spectra.



semiconductor lasers

JPL and NASA have a long history of flying tunable diode laser (TDL) spectrometers on Earth and recently planetary missions to detect and measure atmospheric and other volatile gases. An in situ tunable laser spectrometer (TLS) has been developed at JPL and is currently being integrated into the Sample Analysis at Mars Instrument Suite, part of the Mars Science Laboratory scheduled for launch in 2011. TLS, which uses two mid-IR lasers operating near 3.0 µm, will measure the isotope composition of atmospheric and volatile gases with very high sensitivity and selectivity on Mars.

Despite the remarkable instrument capabilities of TLS, the performance of next-generation tunable diode laser (TDL) spectrometers can be greatly improved by the development of low power consumption, room temperature operation mid-IR optical sources with optimized performance at wavelengths that can be used to measure isotopes of gases like methane, carbon dioxide, carbon monoxide, hydrogen cyanide, and acetylene.

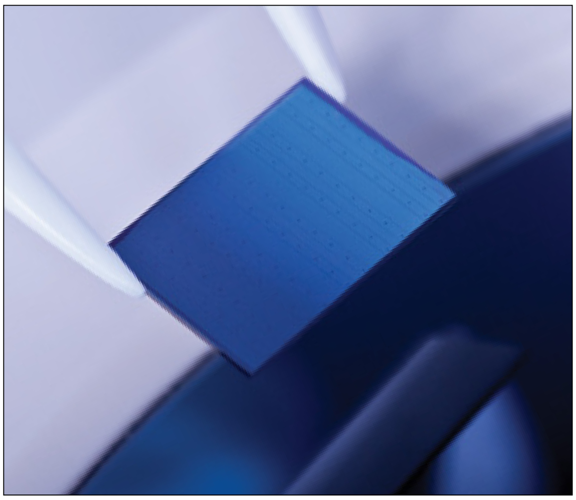
In addition to the planetary atmospheric studies, tunable diode laser spectrometers could have a very important role in life support and environmental monitoring and control in long-duration human space missions planned for the future, which include extended stays aboard the International Space Station, an expedition to Mars, and return trips to the moon.

The current research and development work on semiconductor lasers at MDL is focused in three areas: (1) GaSb-type-I semiconductor diode lasers; (2) quantum cascade lasers (QCL); and (3) interband cascade (IC) lasers.

GaSb-type-I semiconductor diode lasers

We are developing GaSb-type-I low power consumption room temperature semiconductor diode lasers operating in the 3.0–3.5 µm spectral range in collaboration with professor Belenky's group at Stony Brook University. In this research, we are working to combine the recent breakthroughs in the development of antimonide-based mid-IR diode laser technology at Stony Brook University and JPL's unique design of laterally coupled subwavelength grating structures to develop single-frequency distributed feedback (DFB) diode lasers operating above room temperature with extremely low power consumption and high optical power. Compared to the state-of-the-art

semiconductor lasers year-in-review



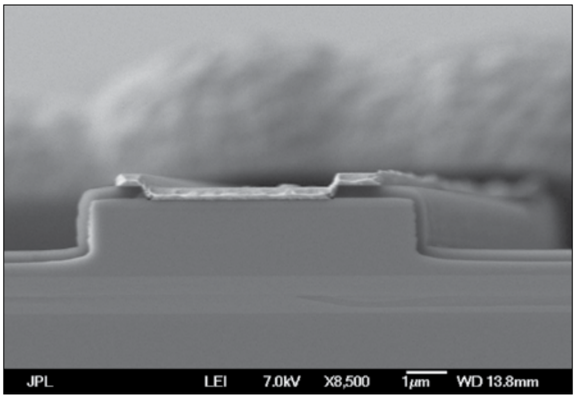
An in-process GaSb-based laser diode wafer with a silicon nitride ridge-patterned mask for dry etching in a chlorine ICP. The mask is patterned for 8, 10, 12, and 14 μm ridges.

interband cascade integrated in the TLS instrument, the proposed lasers should have at least 40 K higher operational temperatures, two orders of magnitude better optical/electrical power conversion efficiency, and much improved reliability and lifetime.

In this project, the first ridge waveguide type-I quantum-well GaSb-based diode lasers operating at room temperatures in the spectral region near 3.15 μm were designed and fabricated. In these devices, the active region is composed of three InGaAsSb quantum wells embedded into a quinary AlInGaAsSb barrier material to promote carrier confinement. Lasers generated 9 mW of the continuous wave output power at 3.16 μm in a diffraction-limited beam at 20˚C. Devices operate in a continuous wave regime up to 40˚C producing above 1 mW of power at wavelengths above 3.2 μm. The successful continuation of this work will enable a new generation of compact tunable diode laser spectrometers (TDLS) with lower power consumption, reduced complexity, and significantly reduced development costs compared to TLS/MSL.

quantum cascade lasers (QCL)

We are developing InP-based low power consumption quantum cascade lasers (QCL) in the 4.0–4.6 micron spectral range in collaboration with Professor Clair Gmalch's group at Princeton University. In this work, we will utilize the recent progress in QCL made by Princeton University to realize quantum cascade lasers operating at room temperature with power consumption of less than 1 W and output power greater than 10 mW. The high-performing devices will be realized by combining the recent advances in the design of high wall-plug efficiency quantum cascade lasers based on novel active region architecture with the optimization of ultra-short cavities to produce small, less power consuming quantum cascade lasers.



A scanning electron microscope image of a fully processed, 8 μm laser ridge designed to emit light at 3.1 μm.

Due to the favorable atmospheric properties, mid-infrared (mid-IR) atmospheric transmission windows occupying 3–5 or 8–12 μm spectral bands are of particular interest for realization of high-speed free space optical (FSO) communication.

interband cascade (IC) lasers

Due to the favorable atmospheric properties, mid-infrared (mid-IR) atmospheric transmission windows occupying 3–5 or 8–12 μm spectral bands are of particular interest for realization of high-speed free space optical (FSO) communication. The molecular (Rayleigh) and particulate (Mie) scattering as well as the wavefront propagation phase errors decrease with wavelength and, therefore, the transmission loss of an optical link operating in the mid-IR would be significantly reduced compared to the loss of the optical link at 1.5 μm. In addition, the spectral radiance of the main sources of background radiation in the atmosphere (Sun, Earth, Moon, city lights, etc.) has a pronounced minimum around 3.5 mm, and thus the background noise will be minimized. The progress in the development of mid-IR FSO links has been hindered by the lack of high-speed lasers, optical amplifiers, and detectors operating in the desirable wavelength regions.

Interband cascade (IC) lasers are novel Sb-based semiconductor lasers that have demonstrated high-performance operation in the 3–5 μm wavelength region, including high output power cw operation at high temperatures and high-speed modulation. This progress enables utilization of IC lasers as optical transmitters in free space optical (FSO) communication links operating in the 3–5 μm atmospheric transmission window. In this work, we have fabricated and provided the first experimental evidence that IC lasers can be directly modulated at a frequency of 3.2 GHz and above. Next, we utilized the high-speed IC lasers to realize the FSO link operating in a 3–5 μm atmospheric transmission window and compared its performance with the performance of a near-IR link at different fog conditions using an indoor communication testbed. This work has demonstrated the suitability of IC lasers as a mid-IR light source for high-speed free space optical communication links, and has also demonstrated the advantages of the mid-IR FSO link in fog due to its lower attenuation and scintillation. These results are the first step in the development of a practical mid-IR FSO communication system and are important for the future improvement of mid-IR lasers and detectors.

operating perameters	interband cascade lasers	next generation diode lasers
voltage	6 volts	0.8 volts
current	200 mA	100 mA
operating temperature	-20˚C	>20˚C
total efficiency	<1%	>10%
electrical power	10–20 watts	<1 watt
reliability	moderate	high

MDL is investigating methods for improving properties of UV-visible-NIR detectors using epitaxial non-equilibrium techniques to manipulate atoms' positions, alter bandstructure and interface structures, form quantum dots, and produce high-performance devices.

advanced UV-visible-NIR detectors

The MDL Advanced Detector Arrays and Nanoscience Technologies Group develops high-performance semiconductor imaging detectors for future missions. We use advanced epitaxial techniques for band-structure engineering and interface band engineering to achieve high sensitivity and extend spectral range. The nonequilibrium processes of epitaxial growth allow us to create nanostructures for detector and power device applications. The group positions itself to respond to the needs of future missions in astrophysics, planetary missions, Earth science, and reimbursable areas requiring large UV, optical, and NIR focal plane arrays (FPAs). The group's processes and infrastructure are designed for compatibility with the silicon imaging industry and alignment with the need of future missions.

High-performance imagers in the ultraviolet/optical/near-infrared are required for future missions and instruments under planning. Silicon imagers achieving near ideal performance will be required. To achieve the highest performance possible, back illumination is essential. The delta-doping technique, invented and developed at JPL, offers near ideal performance in this spectral range with 100% internal quantum efficiency and low thermal noise. Using molecular beam epitaxy (MBE), nanometer-scale modifications are made to the device lattice to nanoengineer the surface band structure and modify the spectral response and quantum efficiency. This technology is applicable to many device designs and it is extended to photon counting applications. Our laboratory's end-to-end post-fabrication processing is expanding to high-throughput, high-yield processes for high-performance silicon imagers. The centerpiece of this expansion is a newly acquired and installed silicon MBE that is capable of high-capacity delta doping for back illumination of scientific imagers. Beyond meeting these needs, we look to future opportunities requiring device and detector development using other group IV material systems. Similar techniques are being developed in our group for high-efficiency, high-gain III-Nitride imagers and photocathodes. Among other devices, instruments, and processes under development in the group are wavelength tunable detectors, a time-resolved Raman spectrometer using a time-resolved streak detector, and atomic layer deposition (ALD) for advanced optical coatings.

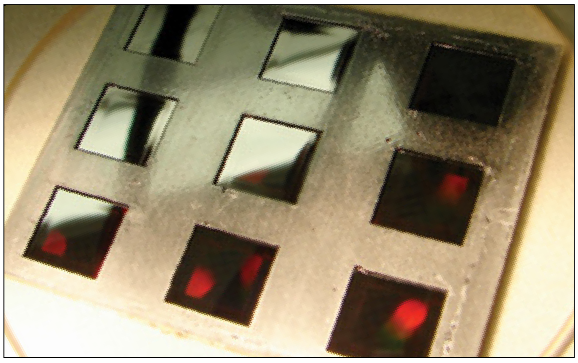
advanced UV-visible-NIR detectors year-in-review

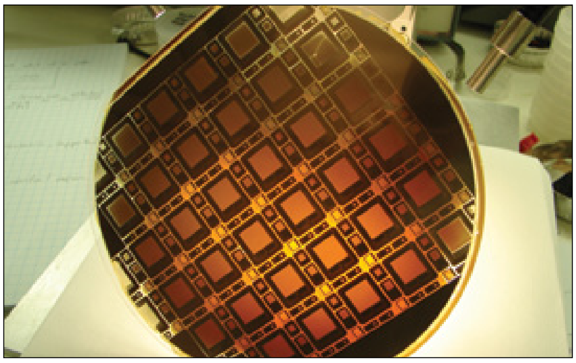
end-to-end post-fabrication processing for high-performance silicon imagers

8-inch silicon molecular beam epitaxy for high-throughput processing of UV/optical/NIR silicon imaging arrays: 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 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 new large wafer capacity with multiwafer capability provides high-throughput processing required for producing a large number of large-area arrays to populate future large FPAs. This MBE is a unique capability that was custom built for JPL. The machine was delivered to JPL and is going through final integration and installation with calibration and processing commencing in the 2010 calendar year.

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.

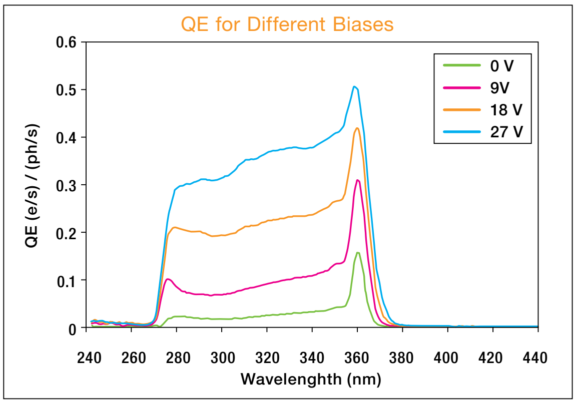
In collaboration with Rochester Institute of Technology and University of Rochester we have embarked on the development of a back-illuminated, thinned, delta-doped CMOS imager for planetary applications. These detectors

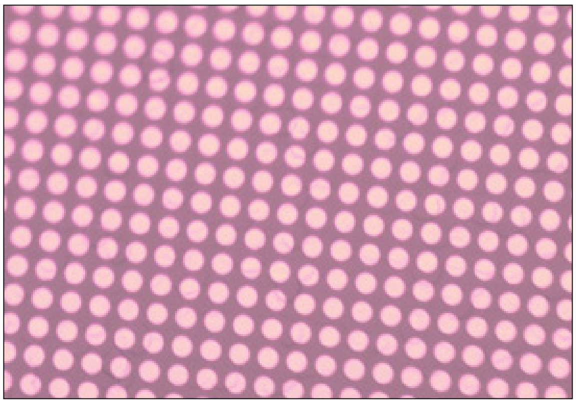




Back-illuminated CMOS imagers allow high sensitivity through thinning and delta doping. Typically, in CMOS imagers, part of the pixel area is devoted to electronics. Back-illumination enables a 100% fill factor by restoring the lost real estate back to sensing light. **Left:** A 6-inch wafer containing JPL-designed CMOS imagers thinned to a transparent 6-micron thickness, allowing light to transmit through the wafer giving the red hue to the wafer. **Right:** A raft of multimegapixel CMOS imagers on their processing journey to be thinned to 5-micron membranes.

In typical CMOS imager design, part of the pixel area is devoted to electronics. Back-illumination enables a 100% fill factor by restoring the lost real estate back to sensing light.





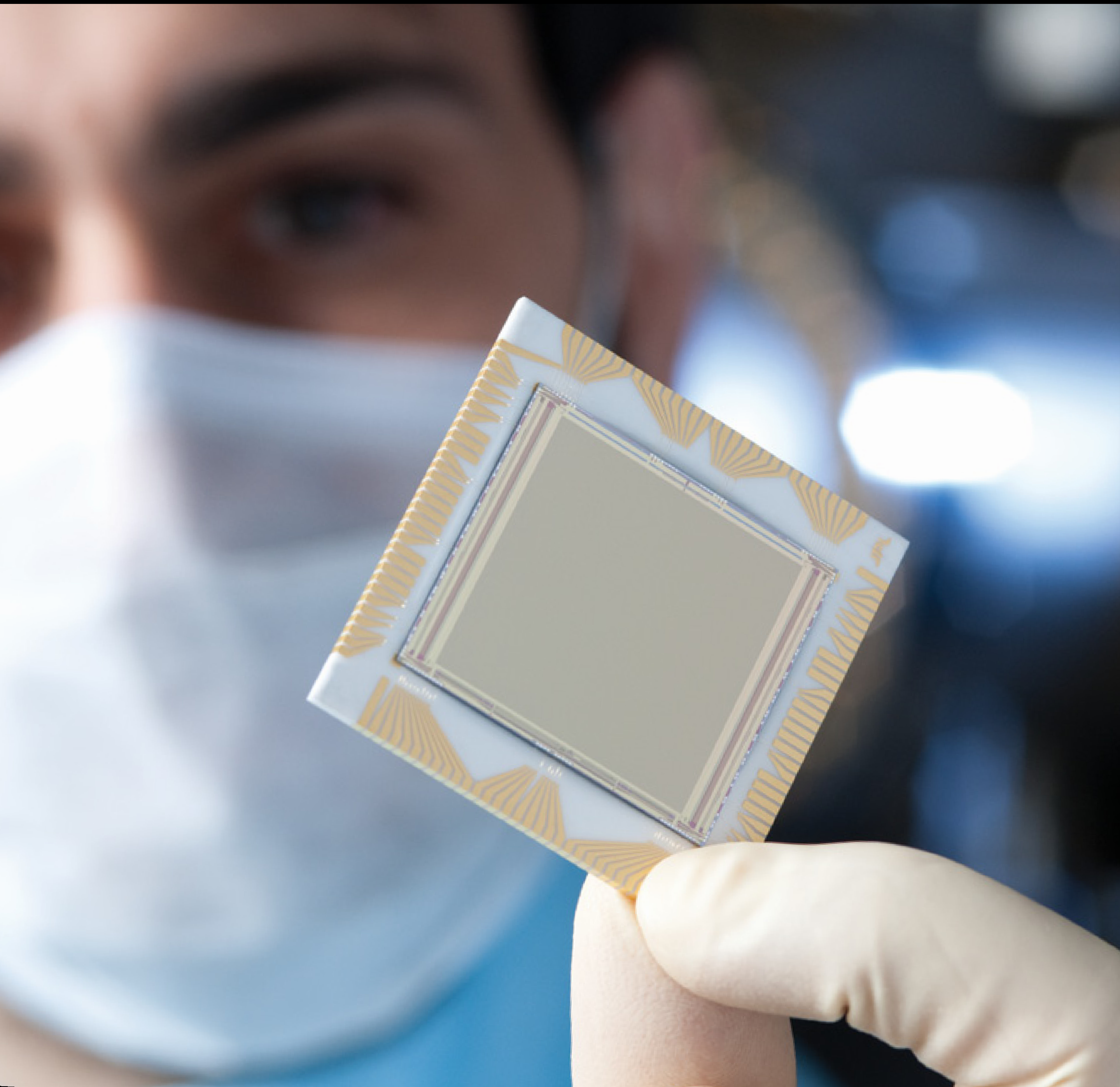
Left: Quantum efficiency of III-N arrays as a function of bias showing high QE and excellent visible light rejection.
Right: Array of III-N diodes produced for process and growth optimization.

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.

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 focused on the development of nitride processing technologies, hybridization schemes, and materials screening infrastructure for the construction of large-format detector arrays. The figure above right shows an 8x8 250-μm pixel array used for nitride material screening. Indium bump reflow process were developed for the optimization of our hybridization process. An array of rectangular indium bumps are exposed to a hydrogen plasma, and reflowed until they 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.

JPL's Infrared Photonics Technology Group is engaged in the development of novel infrared detectors, multiband focal plane arrays, and solar cells for NASA and DoD applications.



infrared photonics

Visible light spanning the wavelength range from blue (~0.4 μm) to red (~0.7 μm) is just a tiny slice of the electromagnetic spectrum. While an enormous wealth of scientific information can be, and is, obtained through the imaging and spectroscopy of objects in visible light, the invisible portion of the spectrum can be harvested to yield both more detailed and new information. Objects that are invisible to the human eye may be visible at other wavelengths. For instance, an object at room temperature (~300 K) and in complete darkness may be completely invisible to the human eye; but its temperature will make it glow in the infrared (at wavelengths longer than the 0.7 μm wavelength of red light), shining brightest at an infrared (IR) wavelength of around 8.5 μm. Thus, in the early nineties JPL formed an Infrared Photonics Technology Group (IRPTG) at MDL to develop novel infrared technologies for dual-use applications. Currently IRPTG consists of 22 group members and is lead by Dr. Sarath Gunapala. 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-inch wafers and are easier to grow and to process into large-area arrays.

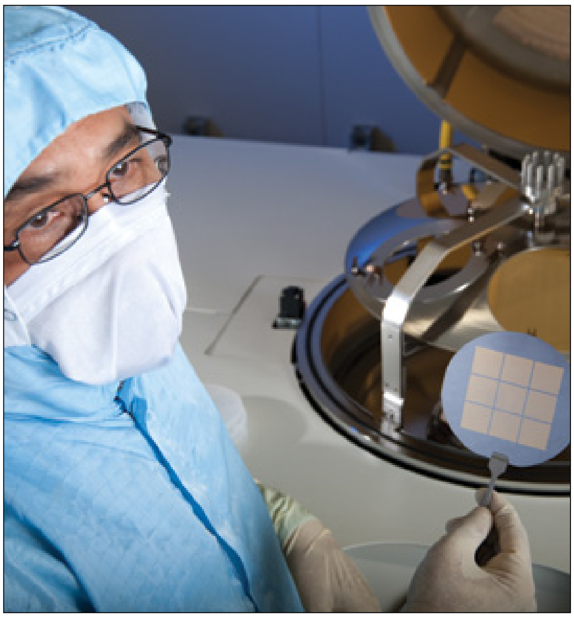
IRPTG is engaged in the development for quantum well infrared photodetectors (QWIPs), quantum dot infrared photodetectors (QDIPs), superlattice, barrier infrared detectors (BIRDs) and large-area focal plane arrays based on these detector technologies for NASA, defense, and intelligence applications. IRPTG has produced over 200 publications and granted 15 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

infrared photonics year-in-review

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.

antimonide-based infrared detectors and focal plane arrays

The closely lattice-matched material system of InAs, GaSb, and AlSb, commonly referred to as the 6.1 Å



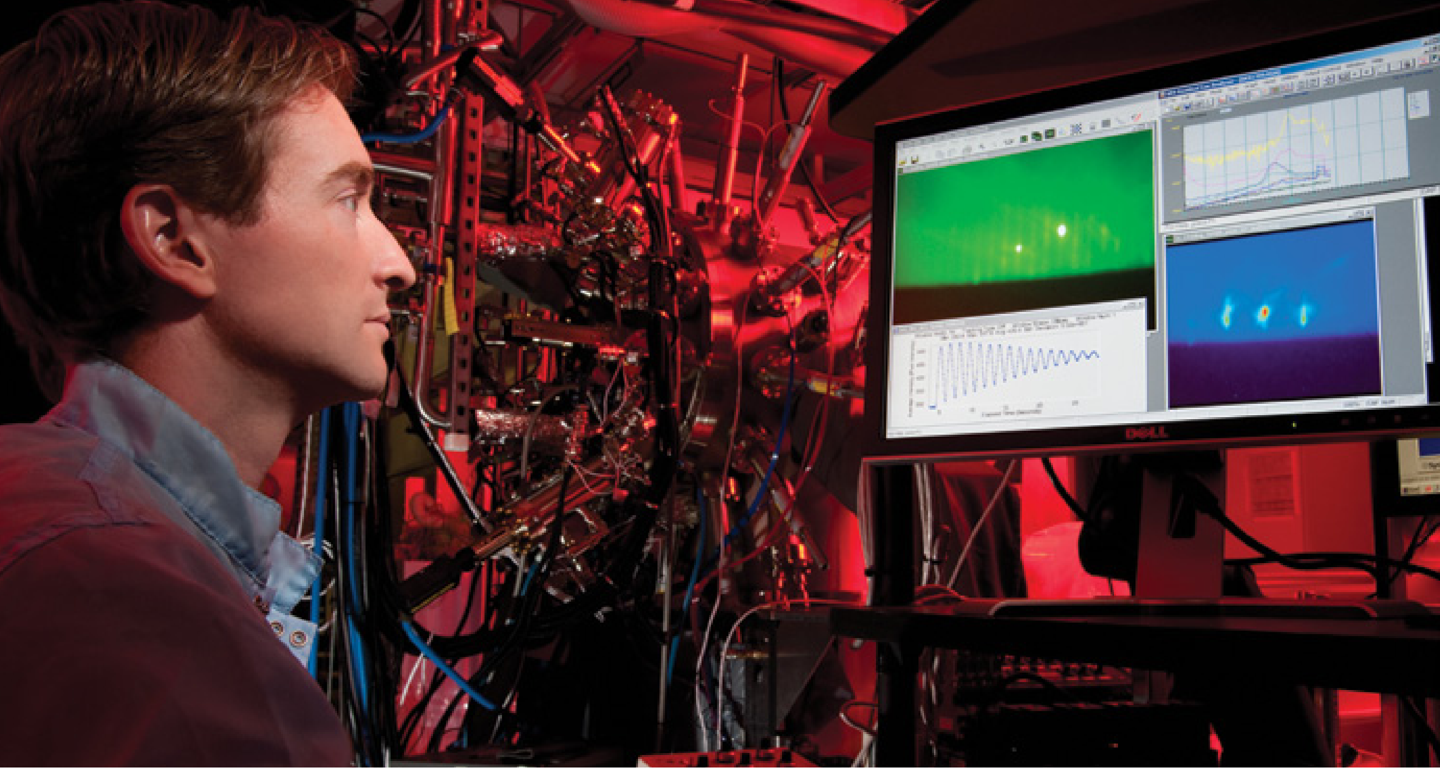
A 4-inch GaSb wafer with nine megapixel LWIR superlattice focal planes in the procees of being loaded into an indium evaporator. It deposits the indium bumps on infrared detector arrays and silicon readout integrated circuits for the focal plane array hybridization process.

material system, has emerged as a fertile ground for the development of new infrared detectors. The flexibility of the system in simultaneously permitting type-I, type-II staggered, and type-II broken-gap band alignments has been the basis for many novel, high-performance heterostructure devices in recent years, including the GaInSb/InAs type-II strained layer superlattice infrared detectors. The type-II superlattice design promises optical properties comparable to HgCdTe, better uniformity, reduced tunneling currents, suppressed Auger recombination, and normal incidence operation. Recently the JPL Infrared Photonics Technology Group demonstrated a 10 μm cutoff device by incorporating electron-blocking and hole-blocking unipolar barriers. This device has shown 300K BLIP operation with f/2 optics at 87 K with blackbody D* of 1.1×10^{11} Jones.

The antimonide material system also allows for the design of high-performance barrier infrared detector (BIRD) structures. Developmental arrays based on superlattices in the long-wave infrared (LWIR) and barrier infrared detector material in the mid-wave infrared (MWIR) have also been demonstrated. High quantum efficiency (QE) LWIR superlattice detectors with a 77K RoA value of over 1000 Ohm-cm^2 have been demonstrated and fabricated into 256x256 arrays. In addition, 640x512 MWIR BIRD arrays have been fabricated showing high QE and excellent imaging quality with a long-wavelength cutoff of 4.2 μm. We have also demonstrated a megapixel MWIR imaging array based on superlattice diodes.

dual-band quantum well infrared photodetector (QWIP) focal plane arrays

Quantum well infrared photodetectors (QWIPs) are well known for their stability, high pixel-pixel unifor-



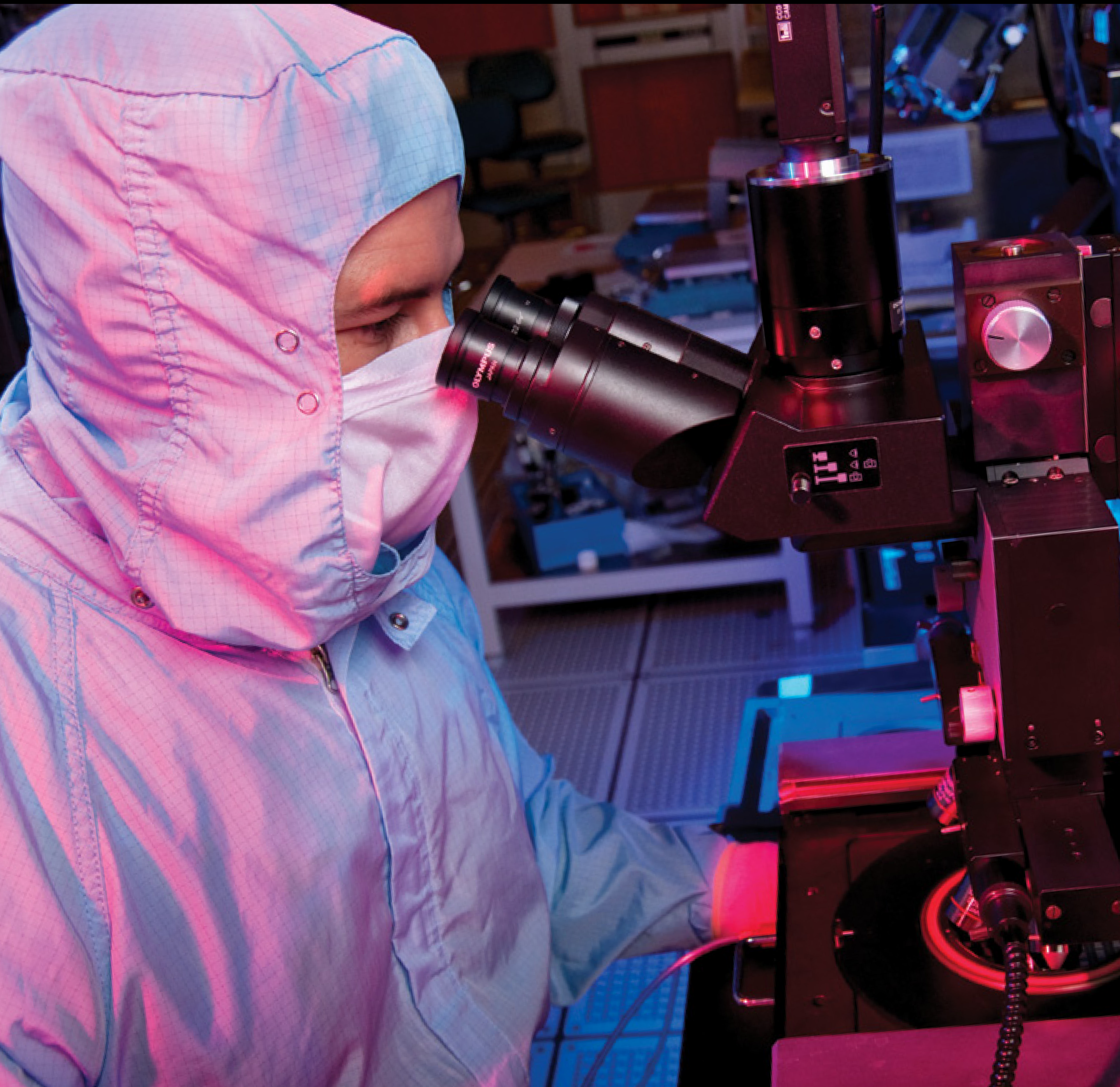
In 2009 JPL's Infrared Photonics Technology Group demonstrated the first megapixel dual-band pixel co-located simultaneously readable QWIP FPA.

mity, and high pixel operability, which are quintessential parameters for large-area imaging arrays. In 2009 JPL's Infrared Photonics Technology Group demonstrated the first megapixel dual-band pixel co-located simultaneously readable QWIP FPA. This dual-band QWIP device is based on a 4–5-micron MWIR and 7.5–9-micron LWIR QWIP devices separated by a 0.5-micron thick, heavily doped, n-type GaAs layer. Both device structures and heavily doped contact layers were grown in situ during a single growth run using molecular beam epitaxy.The photosensitive MQW region of each QWIP device is transparent at other wavelengths, which is an important advantage over conventional interband detectors. This spectral transparency makes QWIPs ideally suited for dual-band FPAs with negligible spectral cross-talk. Megapixel dual-band QWIP detector arrays were fabricated using stepper-based photolithography, ICP dry etching, and e-beam metal evaporation processes developed at the MDL. These detector arrays were hybridized with silicon complementary metal–oxide–semiconductor (CMOS)–based direct injection megapixel readout integrated circuits using an indium bump bonding technique. A selected dual-band megapixel QWIP FPA has been mounted onto the cold finger of a liquid pore-fill dewar, and the FPA was cooled to 70 K. The FPA was back-illuminated through the flat thinned substrate membrane (thickness 500 Å). This initial array gave good images, with 98% of the pixels working, which is excellent compared to the difficulty in the fabrication process of this pixel co-registered simultaneously readable dual-band QWIP FPA. Video images were taken at a frame rate of 30 Hz at temperatures as high as T = 70 K, using two readout integrated circuit (ROIC) capacitors having charge capacities of 3.4×10^6 and 13.6×10^6 electrons for the MWIR and LWIR bands, respectively. The pixel pitch of the array is 30 microns and dimensions of the FPA are 34×39 mm^2. The initial dual-band megapixel QWIP FPAs were cooled to 68 K operating temperature. The preliminary data taken from the first megapixel QWIP FPA has shown system NEΔT of 27 and 40 mK for MWIR and LWIR bands, respectively.

SPIE defense and security symposium

Sarath Gunapala organized and chaired a special session on "Infrared Activities at JPL" session in the Infrared Technology and Application XXXV Conference at the SPIE Defense and Security 2009 Symposium held in Orlando, FL, April 2009. Six invited presentations were given at this well-attended session, which gave an excellent visibility for JPL infrared technologies.

JPL has been a pioneer in the development of superconducting detectors for far-infrared/submillimeter astrophysics for 25 years.



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 in ground-based telescopes around the world, including the Caltech Submillimeter Observatory, the Owens Valley Radio Observatory, and the Smithsonian Astrophysical Observatory's Submillimeter Array. MDL-fabricated SIS mixers have also flown on NASA's Kuiper Airborne Observatory, and will also fly on the CASIMIR instrument on NASA's Stratospheric Observatory for Far-Infrared Astronomy (SOFIA), and were launched in 2009 on the HIFI instrument of ESA's Herschel Space Observatory. JPL's SIS mixers were the first to operate at frequencies higher than 1 THz with noise temperatures below 1000 K, a technology breakthrough that enabled the HIFI instrument. SIS mixers are also being developed for a future Earth science mission, the Global Atmospheric Chemistry Mission. Spinoffs of this technology include superconducting qubits for quantum computation, superconducting nanowire single-photon detectors for optical communications, and the quantum capacitance detector.

More recent development efforts have been on large-format arrays of direct detectors for spectroscopy, imaging, and polarimetry. This effort began with the development of spider-web bolometers, which were launched in 2009 on the HIFI instrument on ESA's Planck mission and on the SPIRE instrument on ESA's Herschel Space Observatory for studies of anisotropies in the cosmic microwave background radiation. Current efforts are on replacing the Ge thermistors used in the original spider-web bolometers with superconducting transition-edge sensors (TES), enabling larger format arrays. TES arrays have been delivered for the BICEP II instrument at the South Pole, and are currently being delivered for the SPIDER balloon-borne telescope. These are important technology demonstrations that are milestones on the road to future space missions such as the BLISS instrument on the Japanese SPICA mission, EPIC/CMB-Pol, and CALISTO/SAFIR for studies

superconducting materials and devices year-in-review

including the inflation that occurred in the earliest stages of the Big Bang and star and galaxy formation in the early universe.

Microwave kinetic inductance detectors (MKIDs) are a new detector concept invented at Caltech and JPL. These are being developed primarily for applications similar to those of TES arrays, and also for optical, x-ray, and dark-matter detectors. Compared to TES arrays, the main advantages are the relative ease of fabrication and signal readout, though to date the more mature TES array technology has demonstrated higher sensitivity. MKID arrays have been demonstrated in a submillimeter camera on the Caltech Submillimeter Observatory, and are also being developed for an optical camera for the 200-inch telescope on Mount Palomar.

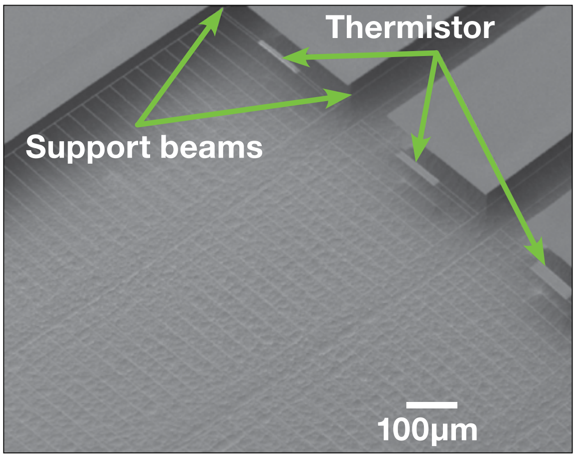
Uncooled thermopile infrared detector arrays were developed for the Mars Climate Sounder instrument on the Mars Reconnaissance Orbiter mission launched in 2005. Spare MCS arrays were also launched on the Lunar Diviner Radiometer instrument on the Lunar Reconnaissance Orbiter mission on June 18, 2009. In a new task this year, the capability to make these detectors is being restarted. This new task is developing uncooled thermopile arrays for a thermal imaging instrument in a future mission to Europa.

SIS mixers

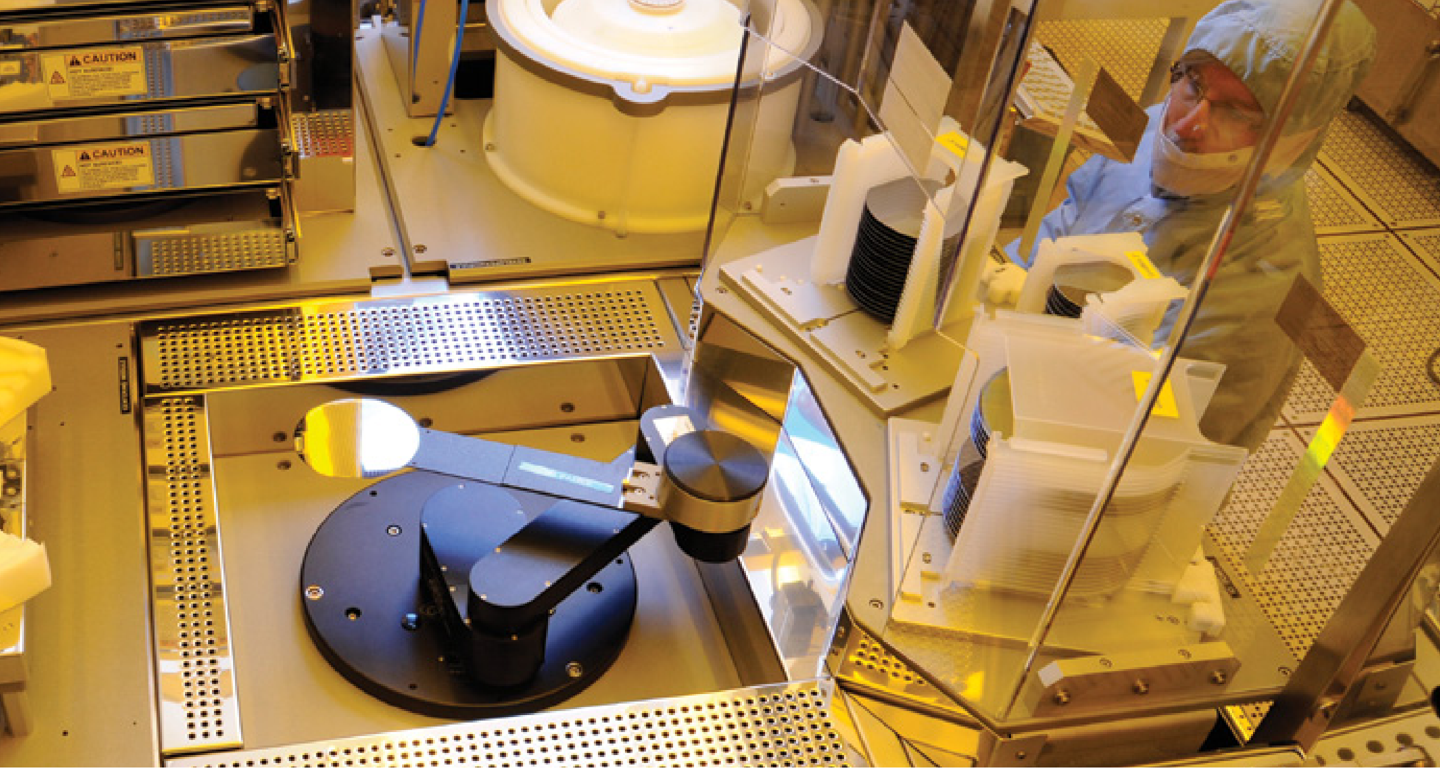
SIS mixers are currently being delivered for the Smithsonian Astrophysical Observatory's Submillimeter Array in Hawaii, for the CASIMIR instrument on SOFIA, for the Stratospheric Terahertz Observatory balloon mission, and are also being developed for the Global Atmospheric Composition Mission concept. The latter is an Earth science mission concept to study the chemistry of the upper atmosphere to address questions of climate change, ozone layer stability, and air quality.

TES bolometers

Superconducting transition-edge sensor (TES) bolometers sense small temperature changes that occur when photons are absorbed and converted to heat. The TES bolometers will replace the MDL/JPL-developed spider-web bolometers that have been deployed on numerous ground-based and suborbital balloon telescopes, and that were recently launched on May 14, 2009, on ESA's Planck and Herschel Space Observatory missions. The use of TESs enables arrays with a much larger number of pixels than is practical with spider-web bolometers. TES arrays are being developed for imaging, spectros-



Micrograph of a segment of a 1D TES array being developed for the BLISS instrument on the Japanese SPICA mission. The TES thermistors are on 300 μm x 2000 μm silicon nitride absorbers, suspended (for thermal isolation) with support beams 1000 μm long x 0.25 μm thick x 0.4 μm wide.



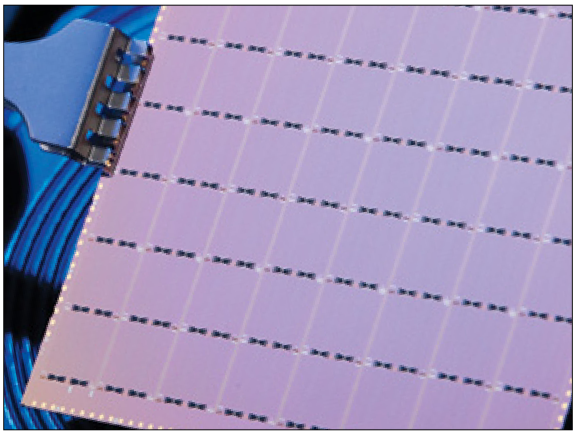
TES arrays are being developed for imaging, spectroscopy, and polarimetry for future missions such as JPL's proposed BLISS instrument for the Japanese SPICA mission, SAFIR, and EPIC/CMB-Pol.

copy, and polarimetry for future missions such as JPL's proposed BLISS instrument for the Japanese SPICA mission, SAFIR (Single-Aperture Far-Infrared observatory), and EPIC/CMB-Pol. As an important milestone to demonstrate the technology, TES arrays are currently being delivered for ground-based (BICEP II, Keck) and balloon (SPIDER) telescopes.

TES arrays for polarimetry have been delivered for the BICEP-II ground-based telescope at the South Pole, and are currently being delivered for the SPIDER balloon-based suborbital telescope and the Keck telescope in Hawaii. These projects will study polarization anisotropy in the cosmic microwave background radiation, and the technology demonstrated on these telescopes is an important milestone in developing detectors for future missions such as BLISS/SPICA, CALISTO/SAFIR, and EPIC/CMB-Pol.

MKIDs

Microwave kinetic inductance detectors (MKIDs) were invented at JPL and Caltech, and are being developed for photon detection from millimeter to X-ray wavelengths. Compared to other superconducting detectors, fabrication, assembly, and signal readout are much simpler for MKIDs, potentially enabling very large arrays for a broad range of future astrophysics missions.



DEMOCAM2 array for a submillimeter camera for the Caltech Submillimeter Observatory. Each pixel consists of a slot array antenna. The power received by each of these antennas is split into 3 bands (1.3 mm, 1.1 mm, and 850 μm) and detected by a separate MKID. A single microwave feedline is used for reading out the entire array.

optical MKID: Arrays of Ta/Al MKID strip detectors are being fabricated for a 64x20 pixel optical camera for the 200-inch Mount Palomar telescope. This technology demonstration is an important milestone in developing detectors for future missions such as SAFIR, Constellation-X, and TPF-C.

superconducting materials and devices year-in-review

submillimeter MKID: In 2009, 6x6 pixel three-color imaging polarimetric arrays were fabricated for DEMOCAM2, a submillimeter camera for the Caltech Submillimeter Observatory. Currently being designed are 24x24 pixel four-color imaging polarimetric arrays for MKIDCAM, a more complex follow-on instrument. These technology demonstrations are in preparation for a six-color submillimeter camera for the Cornell-Caltech Atacama Telescope, and eventually for a ~128x128 pixel imaging polarimeter for the CALISTO/SAFIR flight mission.

SNSPD

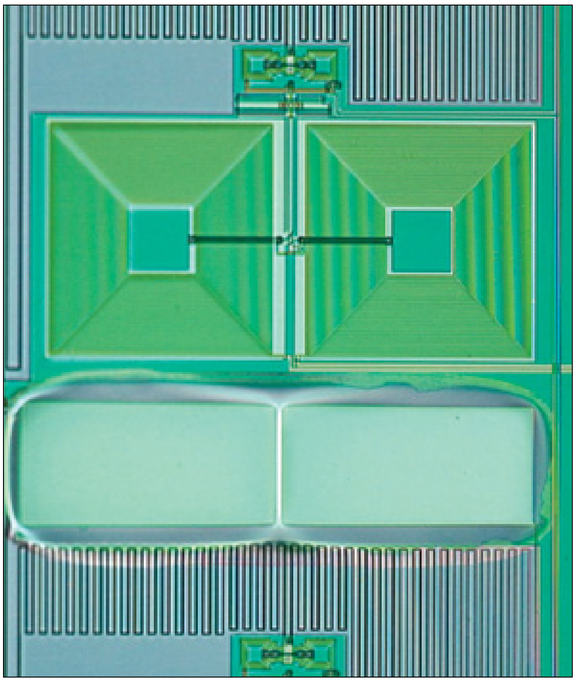
Superconducting nanowire single photon detectors (SNSPDs) are high-speed, high-efficiency, single-photon near-infrared detectors that are being developed for future space-to-ground communication links.

thermopile arrays

Uncooled thermopile infrared detector arrays are broadband detectors that have the advantages compared to uncooled bolometers of low 1/f noise, flat spectral response over a broad band, higher detectivity, and do not require chopping. Although not as sensitive as cooled detectors, the lack of a requirement for cooling makes them more suitable for long-duration planetary missions.

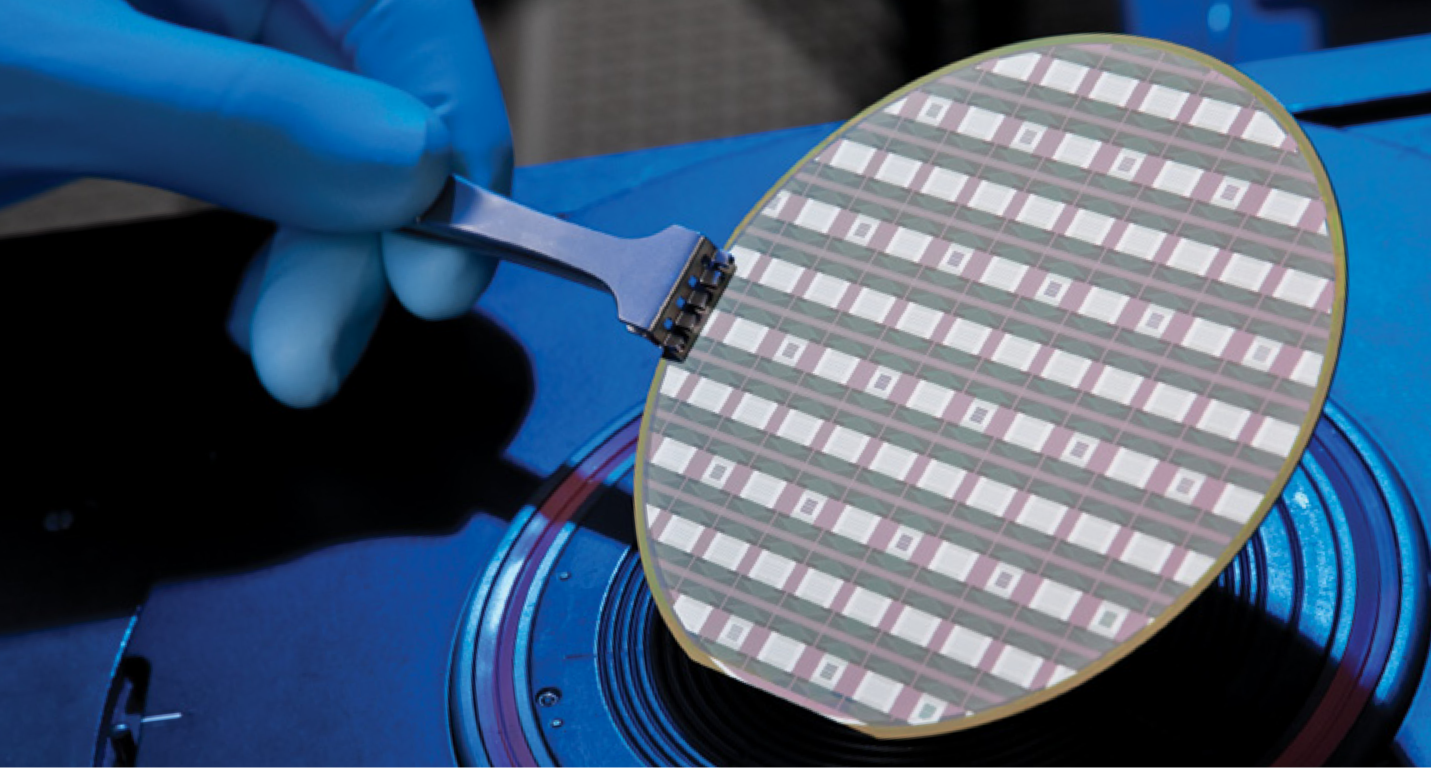
MSQUID

The microwave superconducting quantum interference device (MSQUID) is a new type of readout being developed for TES arrays. Current state-of-the-art SQUID readouts use time domain multiplexing, require a separate feedback line for each pixel, and have a maximum multiplexing factor of 32. Next-generation submillimeter astronomical instruments will have detector arrays with >104 pixels, so scalability of the readout is a serious problem. In the MSQUID concept, the frequency domain multiplexing of MKIDs is extended to superconducting bolometer readouts. Each SQUID is part of a resonant circuit with a unique resonant frequency. Similar to MKIDs, a large number of detector pixels can then be read out with a single transmission line, increasing the multiplexing factor.



Section of a 16-element MSQUID array.

The MSQUID concept was demonstrated in 2009 with an initial prototype four-element array. Each element had a 300 nH input coil for coupling to the signal from a TES. The resonant frequencies were near 10 GHz



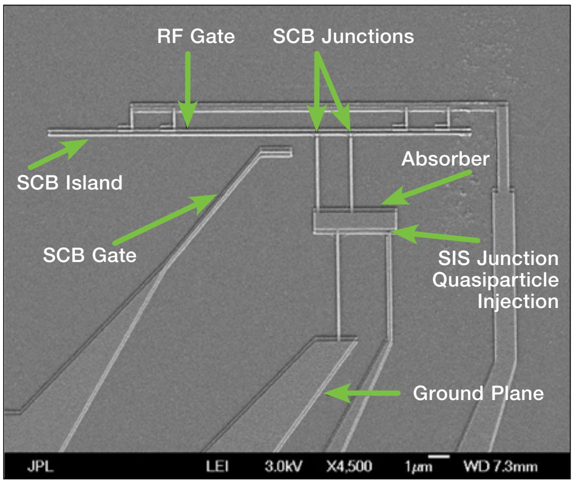
The quantum capacitance detector (QCD) is a new concept for a photodetector based on Cooper-pair breaking in superconductors using a single Cooper-pair box (SCB) as a readout.

and the quality factor Q was ~1000. A 16-element array with improved resonator design for lower noise was also designed and fabricated.

quantum capacitance detector

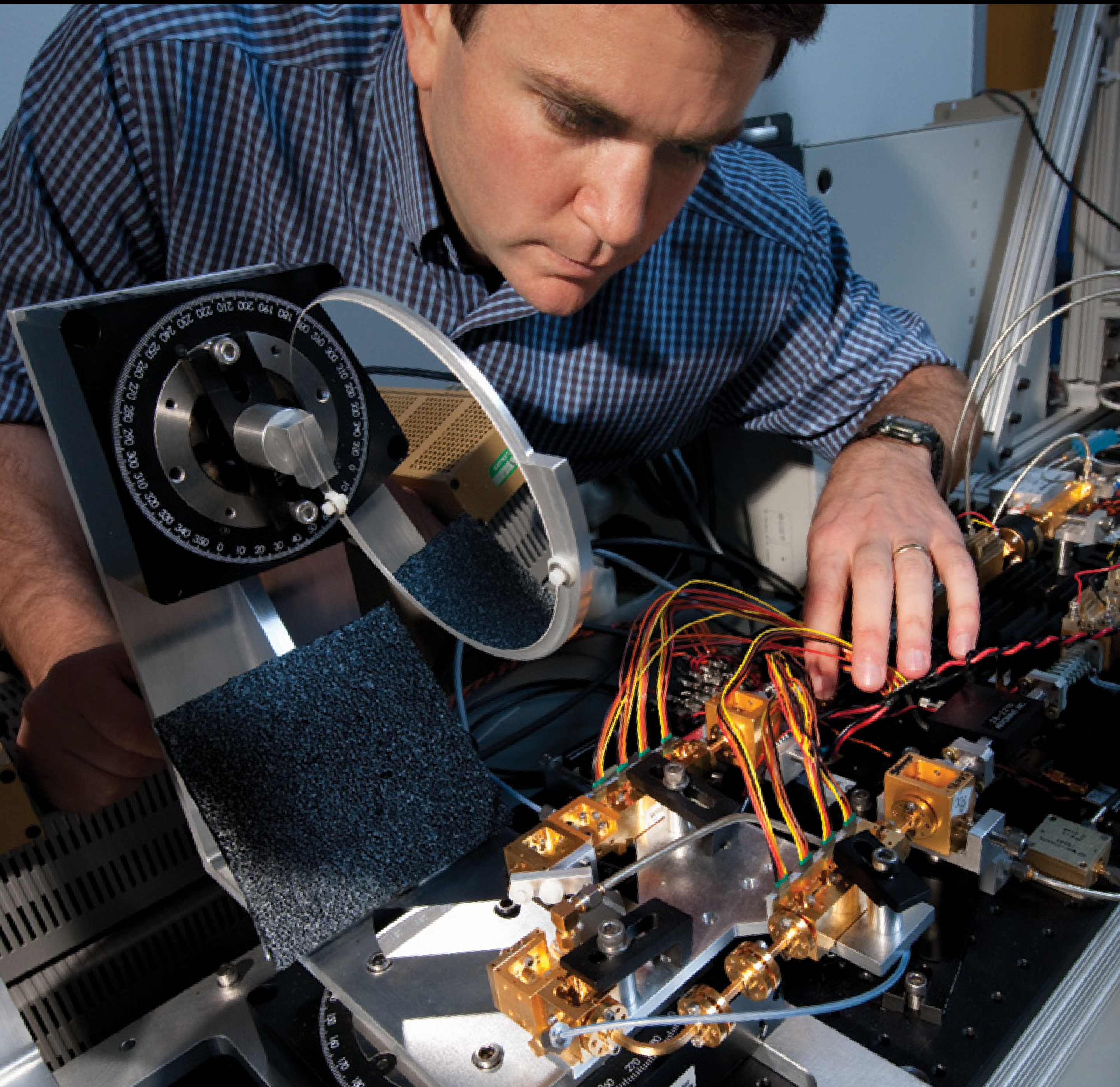
The quantum capacitance detector (QCD) is a new concept for a photodetector based on Cooper-pair breaking in superconductors using a single Cooper-pair box (SCB) as a readout. In this concept, antenna-coupled radiation breaks Cooper pairs in a superconducting absorber and the unpaired electrons then 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 read out with a single RF line and do not require individual bias of each pixel.

A proof of concept for this new type of detector was demonstrated in 2009. A current-biased SIS junction was used to simulate an optical signal, electrically injecting quasiparticles into an absorber; the quantum capacitance of a single Cooper-pair box is proportional to the number of quasiparticles. A noise equivalent power of 1.3×10^{-18} W/Hz$^{1/2}$ at 10^{-16} W loading was measured in this first proof of concept, and a 100x improvement in sensitivity is in principle achievable.



Micrograph of a detector structure used to demonstrate a proof of concept of a quantum capacitance detector. Quasiparticles from a current-biased SIS junction injected into an absorber simulate an optical signal. The quantum capacitance in the single Cooper-pair box (SCB) is proportional to the number of quasiparticles. In this first proof of concept, sensitivity better than MKIDs was demonstrated, and in principle sensitivity comparable to or better than TESs is achievable.

Spectroscopic instruments developed by the Submillimeter-Wave Advanced Technology (SWAT) Group are vital towards accomplishing strategic goals of the Jet Propulsion Laboratory.



submillimeter-wave advanced technologies

The Submillimeter-Wave Advanced Technology 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.

Spectroscopic instruments developed in the group are vital towards accomplishing strategic goals of the Jet Propulsion Laboratory. Technologies developed in our group are mission critical and have enabled the following science in recent years:

- Spectroscopic measurements with our instruments are improving our understanding of Earth's upper atmosphere and helping to quantify the effects of ozone depletion and global warming.
- Spectral line surveys and mapping with our instruments will help explain the origins and behavior of planets, stars, and galaxies.
- Through future high-resolution interferometric observations, our instruments may be able to detect and quantify the chemical constituents of life on extrasolar planets.
- Using in situ measurements, our instruments will be able to identify particular gases and perhaps even liquids and solids in our own atmosphere and on other worlds, enhancing our understanding of the chemistry of planets and planetary bodies within our solar system.

Our unique team of engineers, technologists, and scientists are also continuously involved in inventing and developing new non-space-based applications for submillimeter-wave components in the biomedical, geophysical, material properties, chemical analysis, and threat detection fields.

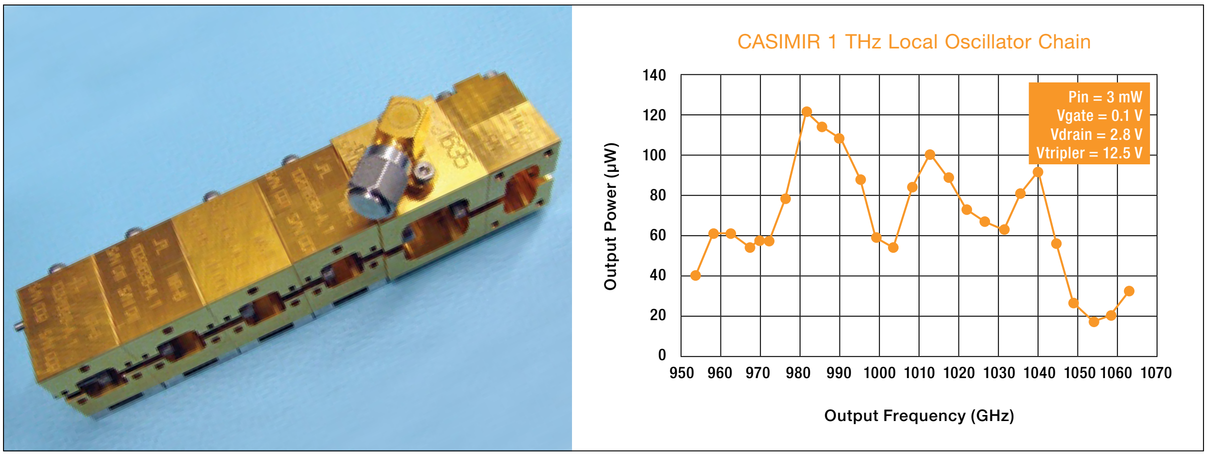
submillimeter-wave advanced technologies year-in-review

broadband multiplied sources

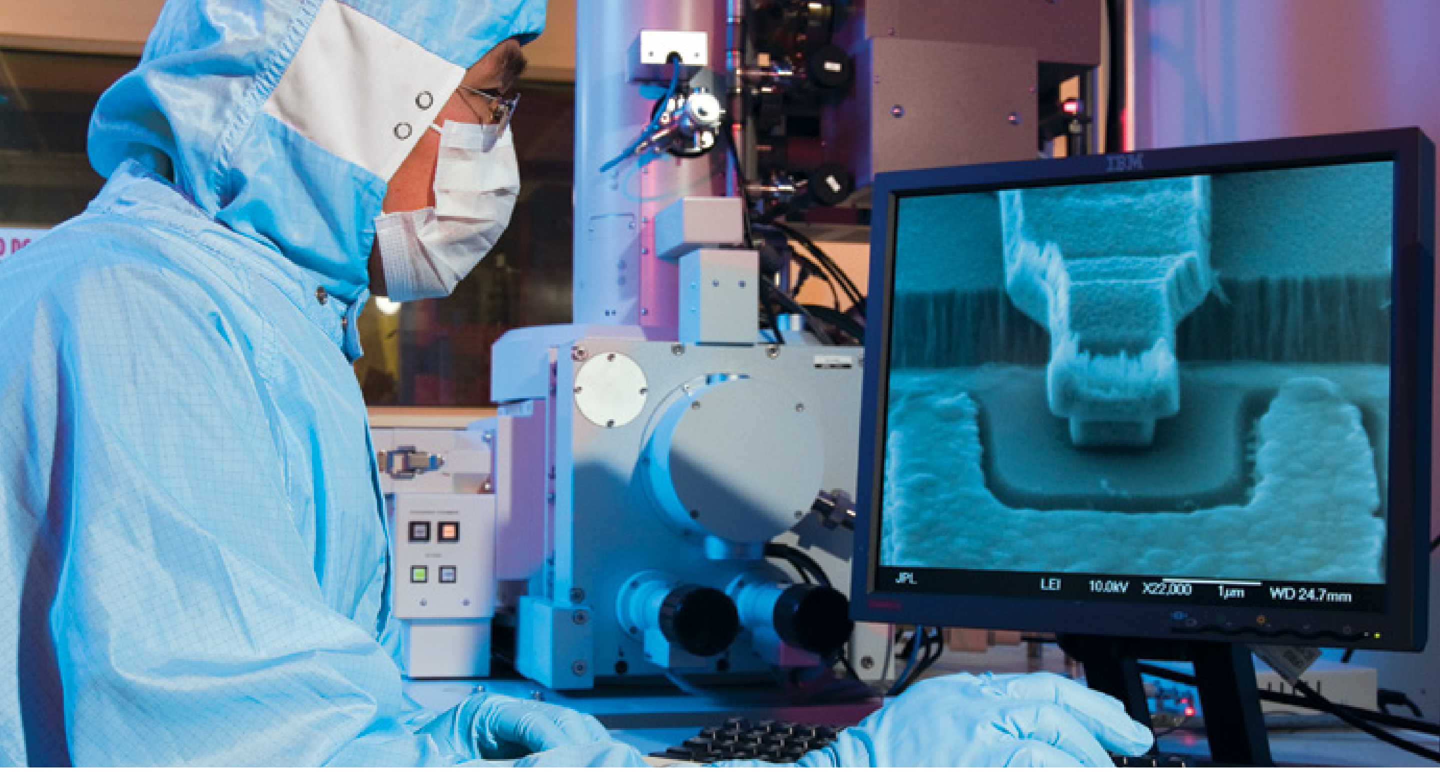
Lack of broadband compact sources continues to be a roadblock for developing applications in the THz range. The new generation of multiplied sources have benefited from the work done for HIFI and can now produce higher power levels. We have also been able to build local oscillator sources for some of the bands that were not covered in HIFI. Below shows an LO chain developed for the Casimir instrument on SOFIA providing more than 40 microwatts of output power in the 970 to 1040 GHz design band. This will enable Casimir to fly an SIS-based receiver on SOFIA. We have also developed the concept of power-combining multiplier chips to enable large input power-handling capability, which in turn directly translates to higher output power levels. This technique has resulted in output power levels in excess of 1 mW at 930 GHz, which is a new world record. This chain will be used as a driver to build up an electronic source at 2700 GHz.

submillimeter-wave schottky diode mixers

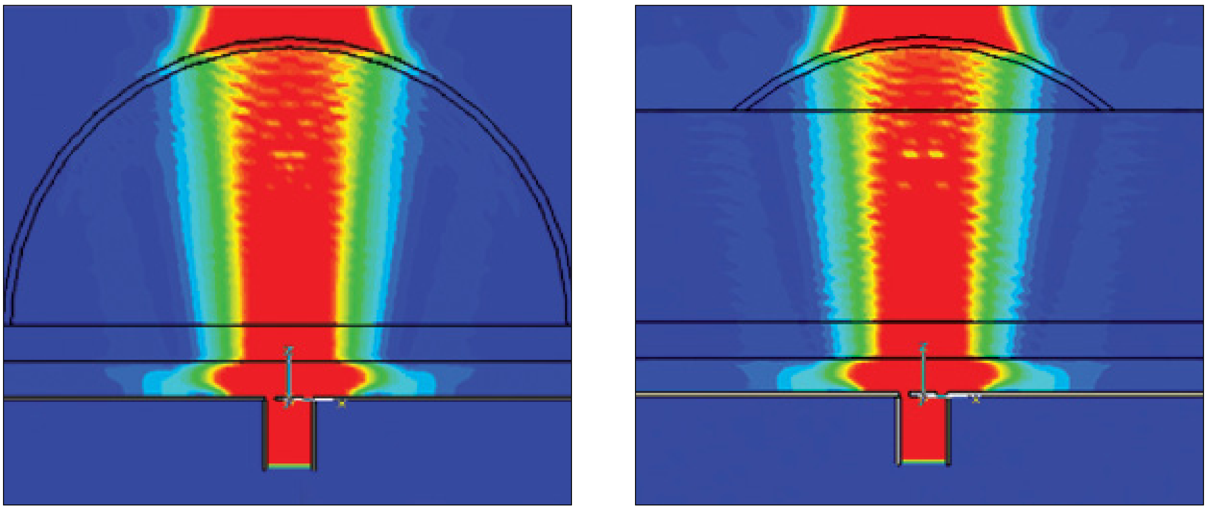
GaAs planar Schottky diode mixers based on a membrane diode process have been used to make a number of different mixer topologies in the 400 to 900 GHz range. The JPL-developed MoMeD (monolithic membrane device) process allows one to incorporate a number of design features at the chip level that allow for increased functionality without sacrificing performance. A balanced fundamental mixer has now been demonstrated in the 530–590 GHz range. To the best of our knowledge this is the first implementation of such a topology with planar diodes at this frequency. This mixer provides better sensitivity compared with subharmonic mixers in the same frequency range, though an additional multiplier stage is required. These mixers are now baselined to be used on future planetary missions.



A 950–1050 GHz LO chain based on a 3x3 implementation developed for the Casimir instrument on SOFIA (PI: Jonas Zmuidzinas).



The JPL-developed MoMeD (monolithic membrane device) process allows one to incorporate a number of design features at the chip level that allow for increased functionality without sacrificing performance.

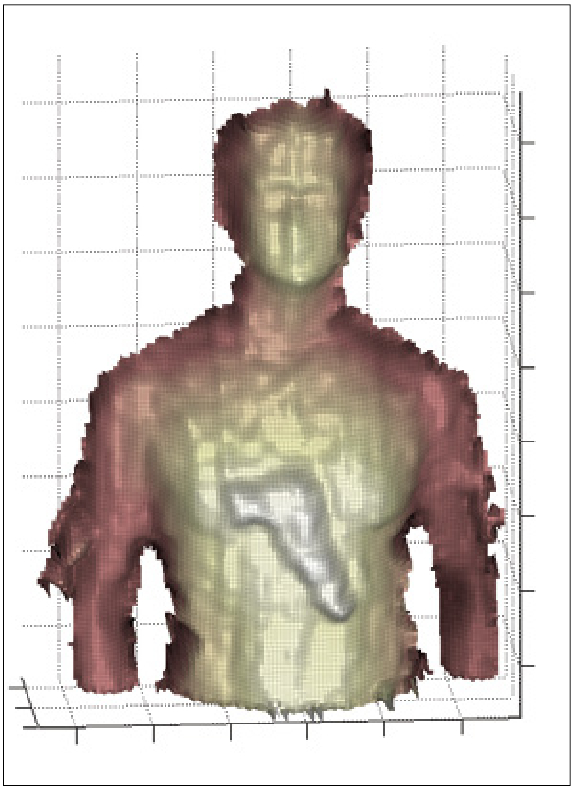


Electric field distribution of a leaky-wave antenna on a silicon lens, showing that the fields are confined to a narrow angle.

silicon micromaching of THz components

microlens work: Submillimeter-wave receivers — both heterodyne and direct detector based, and for spectroscopic as well as imaging applications — require a focused beam from the antenna for high-efficiency measurements. Moreover, future astrophysics, planetary, and Earth observing experiments will require large focal planes with thousands of detectors. Therefore, there is a need to develop integrated antennas with fast beams (higher F#), and most often that requires the use of a lens on planar antennas. We have developed a novel integrated leaky wave antenna on a silicon lens that can be photolithographically fabricated. Using this technique, one can make a large focal plane with antennas and lenses all fabricated monolithically. The key feature of the antenna-lens

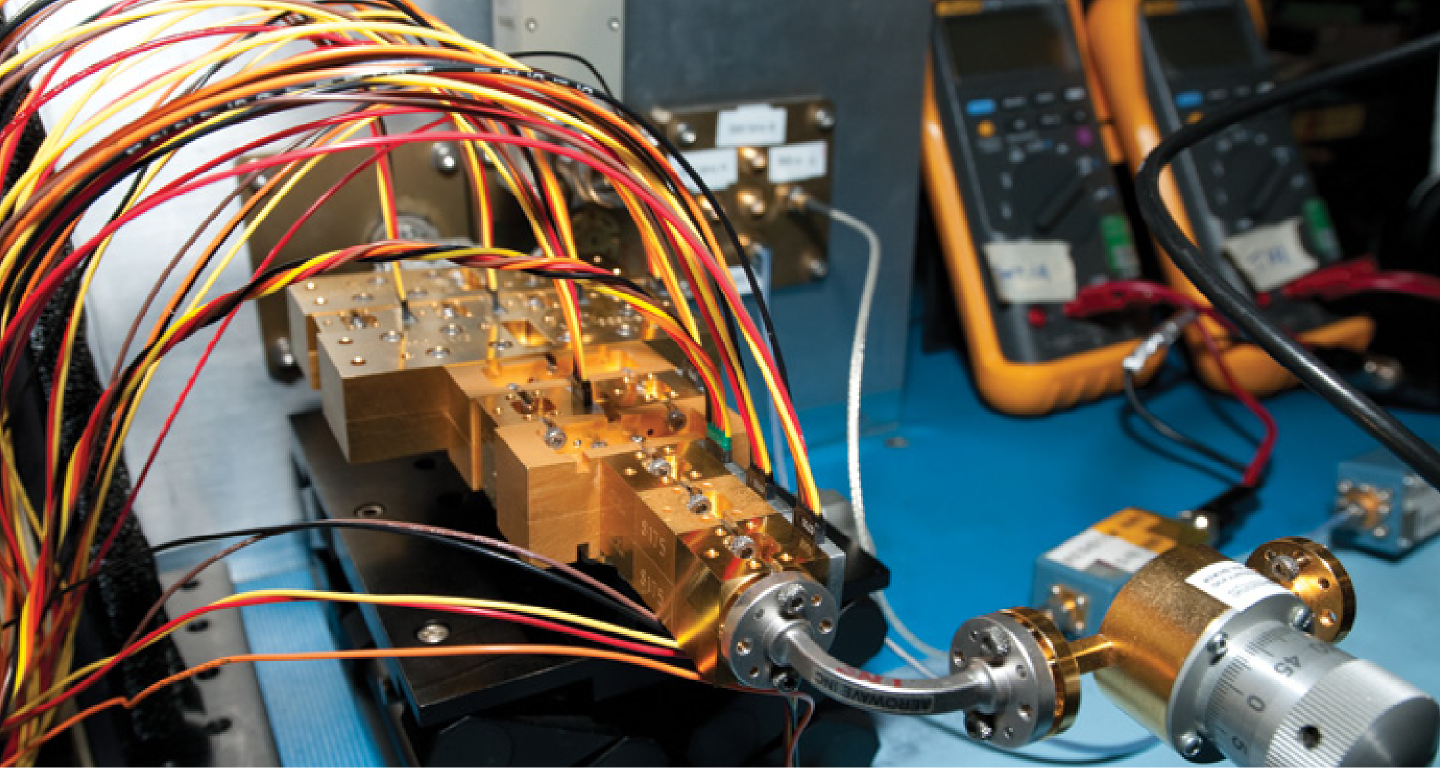
submillimeter-wave advanced technologies year-in-review



THz radar imagery reveals the presence of a replica handgun concealed underneath a shirt at a 4-meter standoff distance. Recently, the radar's imaging time was shortened by a factor of 50 and its standoff range increased from 4 to 25 meters.

design is to have a planar antenna on a substrate where the fields inside the substrate are confined to a narrow angle. Therefore, only a small section of the lens curvature is required to focus the beam of the antenna, and the lens can be developed using a simple photoresist-mask-etching process. The figure on page 35 shows the details of the process and the recent preliminary results.

waveguide components: We have developed silicon micromachined waveguide components in the 325–500 GHz band and are in the process of developing these components for the 500–600 GHz band. One of the key problems in testing micromachined components using silicon has been the interface between them and the measurement equipment. The silicon split blocks need to be perfectly aligned and the face



The active submillimeter imaging project is a Navy-funded effort to develop the technology for detecting concealed weapons or contraband from standoff distances exceeding 20 meters.

contacting the measuring flange needs to be smooth. Else, one can get 10–15 dB of loss at 600 GHz from the gap alone. To solve this problem, we came up with a novel idea of making H-plane bends to bring the flanges on the flat surface of the silicon substrate, and the split waveguide wafers were aligned with metal alignment pins. We fabricated a 40-mm-long waveguide section in silicon using a deep reactive ion etching (DRIE) technique in the WR-2.2 (325–500 GHz) band. The measured performance shows excellent results and was close to simulated predictions. This is the highest frequency silicon micromachined component fabricated in our group and will pave the way for highly integrated, lightweight passive and active components at terahertz frequencies, which will play a major role in future planetary and astrophysics missions.

active submillimeter-wave imaging

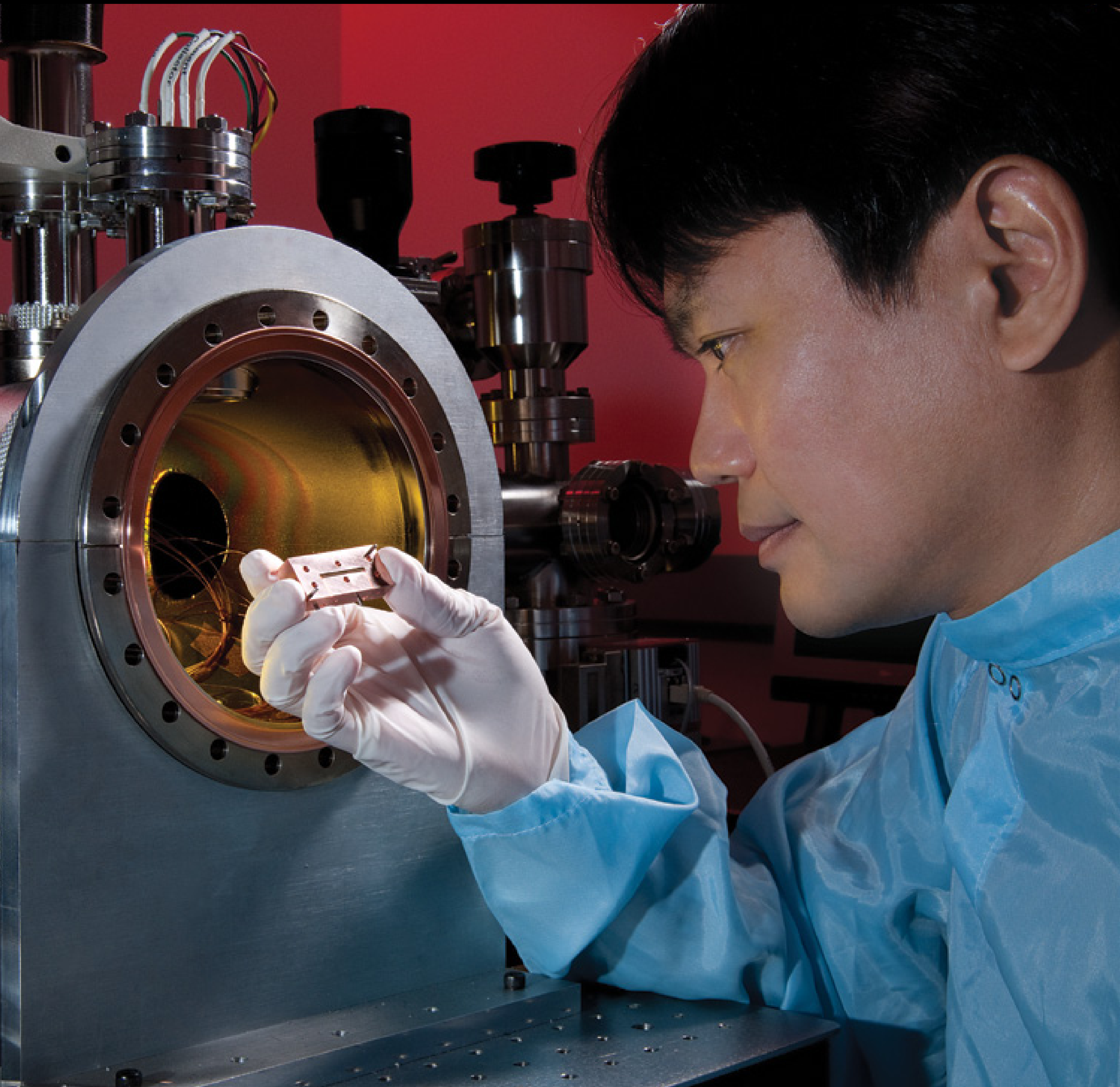
The active submillimeter imaging project is a Navy-funded effort to develop the technology for detecting concealed weapons or contraband from standoff distances exceeding 20 meters. Imaging in the terahertz regime is attractive because wavelengths in the range 100 μm < λ < 1 mm are short enough to provide high resolution with modest apertures, yet long enough to penetrate materials such as cloth or cardboard.

Certain key submillimeter components of the system are fabricated in the MDL. For example, a GaAs-based Schottky-diode tripler operating at 330–345 GHz, and a fundamental balanced mixer, are used to achieve the most sensitive radar signal detection possible. Worldwide, the MDL is one of the few sources of these high-performance devices, and they are crucial to the successful operation of the terahertz imager.

development of multiplexing techniques for large arrays

A novel multiplexed readout technique suitable for large arrays of sensitive transition-edge sensors (e.g., hot-electron nanobolometers (nano-HEBs)) has been demonstrated. The technique uses a specialized microwave superconducting quantum interference device (MSQUID) chip (developed at MDL) and preserves the low-noise detector operation while allowing for a large signal bandwidth (up to 100s kHz) and a large number of detectors (potentially 1000s). The lab work focuses on the demonstration of a small THz camera using an array of sensitive nano-HEBs. Future applications of this technology would be for spectroscopy and infrared calorimetry in space and for large ground-based and suborbital submillimeter imagers.

Application-driven nano and micro devices and techniques, developed through the nano and micro systems effort at MDL, are vital to in situ and remote planetary exploration.



nano and micro systems

This year has seen an expansion in the scope of nano and micro system technologies being developed at MDL. The projects span from the development of a new x-ray-based spectroscopic miniature instrument for molecular finger-printing to a nanostructure-integrated electronic chip cooling technique. Carbon nanotube (CNT)-based devices continue to be one of JPL's main technology strengths, contributing to the extreme environment device portfolio along with GaN devices.

Adapting the principle of the Fourier transform spectroscopic technique used in the infrared to soft x-ray region, a new miniature spectroscopic instrument (FTXR) concept is being researched for potential in situ planetary exploration applications. This novel concept promises increased spectral and spatial resolution in determining the bonding structure of chemically relevant elements in minerals. The enabling component of this instrument is the x-ray interferometer that uses JPL-pioneered perforated membrane technology.

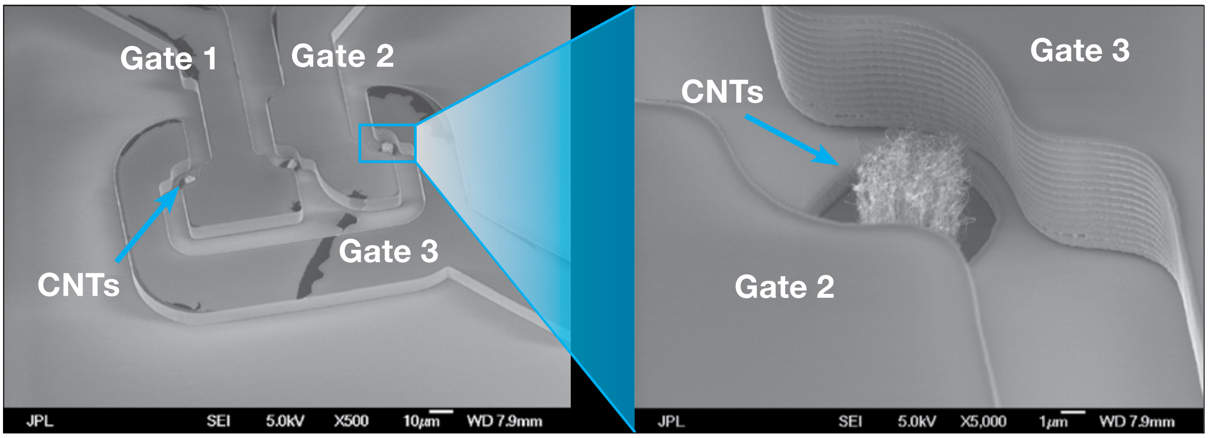
While the FTXR is a project aiming to miniaturize an instrument, "digital" vacuum electronics and the silicon heat pipe array concepts aim to integrate nanostructures on a microplatform to create uniquely capable devices. In both devices, nanostructures such as CNTs or silicon nanotips are integrated with micromachined structures. Some unique coating and packaging technologies have been developed to enable and sometimes enhance performance. Finally, GaN semiconductor devices have continued to show promise as harsh-environment sensors and electronics. New devices have shown operation tolerance to temperatures >450° C and radiation environment of >2 Mrads.

Although nano and micro system activities are predominantly technology development efforts, a pathway to transition some of these ideas to flight is being actively pursued.

"digital" vacuum electronics

A new technology of high-temperature computational components was developed this year for DARPA. This is based on vacuum microelectronics using carbon nanotubes and silicon micromachined vacuum cavities. A three-gate input inverse majority gate device based on a past JPL technol-

nano and micro systems year-in-review



Left: SEM micrograph shows single-bundle device as fabricated. **Right:** Close-up view of the device.

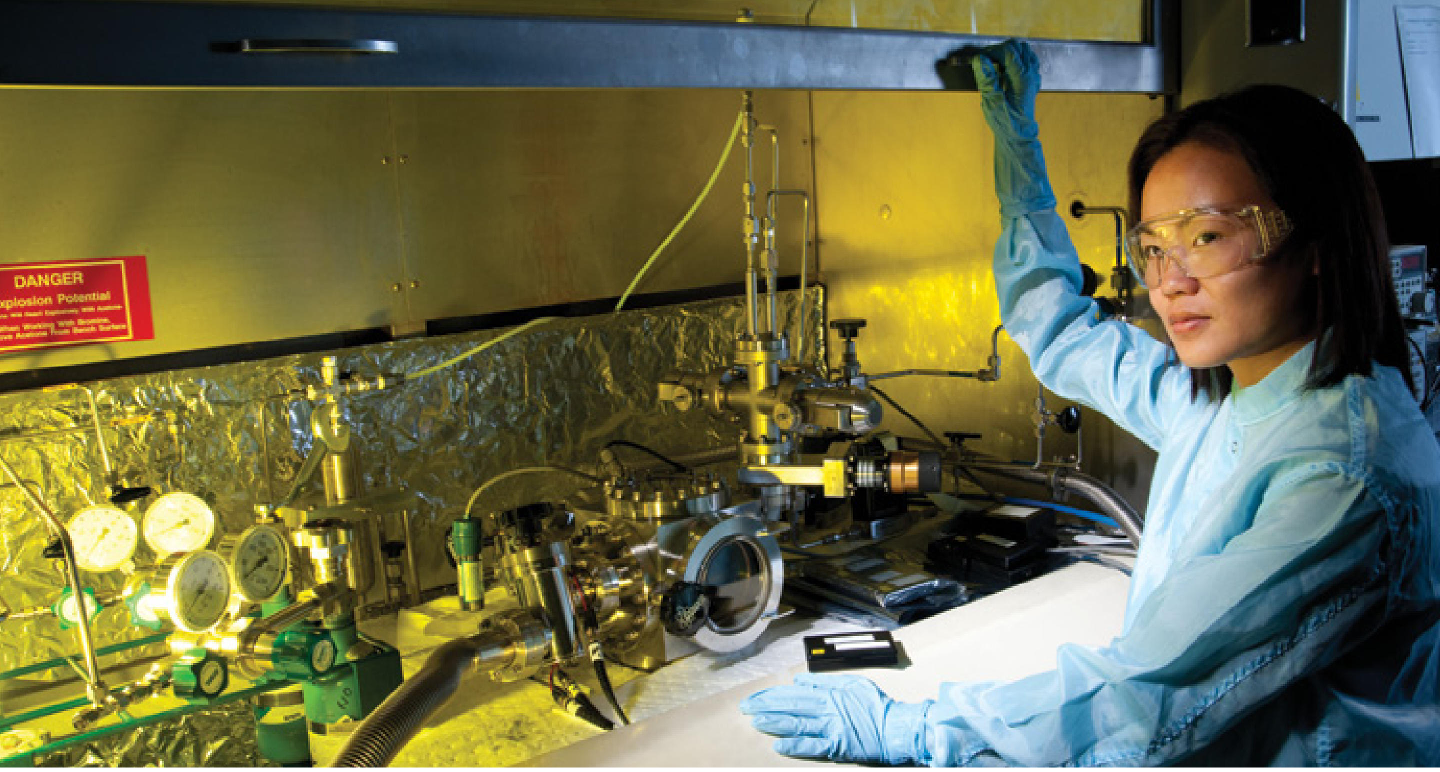
ogy (G4-FET) was designed, fabricated, and tested at room temperature followed by operation at 700° C. The devices successfully performed at high temperature. This is the first development of such a device, and marks the beginning of "digital" vacuum microelectronics. The figure above shows the schematic of the device with three gates, an anode and six field-emitting carbon nanotube bundles. By setting the ON state to be non-zero anode current and the OFF state to be opposite, we have shown that the device requires at least two gates to be ON in order to make the logic state OFF. This leads to the operation of this device as a NAND and a NOR universally programmable logic gate. Other than DC switching, we have also shown the switching operation of the first prototype at 100 Hz. Estimations show more than 100 GHz potential speed and comparable device densities of that of solid-state devices. These devices are also inherently radiation insensitive. This development is of potential interest to the Venus and Jovian science communities, as well as to DoD agencies.

silicon heat pipe array

Improved methods of heat dissipation are required for modern, high-power-density electronic systems. Heat pipes offer a solution to this problem. Heat pipes are passive, self-contained, two-phase heat dissipation devices; heat conducted into the device through a wick structure converts the working fluid into a vapor, which then releases the heat via condensation after being transported away from the heat source. Our silicon heat pipe array utilizes a novel, micro-machined wick with a super hydrophilic coating that ensures complete wetting of the wick structure regardless of orientation, for increased performance and reliability. Because it is made of silicon, it is thermal expansion matched to the die in high-power-density micro-electronics assemblies. This will enable improved thermal management in future advanced spacecraft systems.

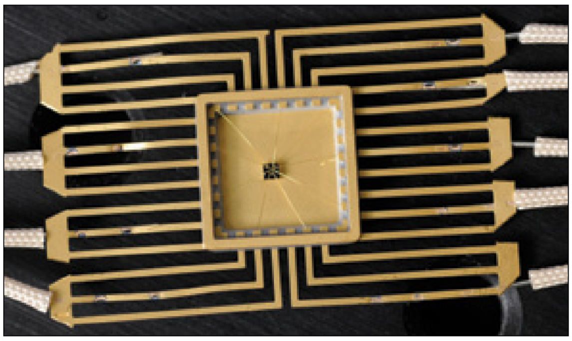
fourier transform x-ray (FTXR) spectral imager

A novel miniature spectral imager in the soft x-ray region is being developed. This novel concept adapts FT



Data acquisition electronics and transmitters are the key electronics that must be operated in harsh planetary environments to condition signals from in situ sensors/detectors and transmit the sensor data to an orbiter or to Earth.

techniques used in IR to the x-ray spectral region, with correspondingly increased spectral and spatial resolution. The crux of the imager is an x-ray interferometer, and the enabling component is a beam-splitting mirror. We have designed and prepared beam splitters based on JPL-pioneered perforated membrane technology. The fabricated 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. Applications for NASA include the determination of bonding structure of chemically relevant elements in minerals; applications for DOE and NIH include fingerprinting molecular structures.

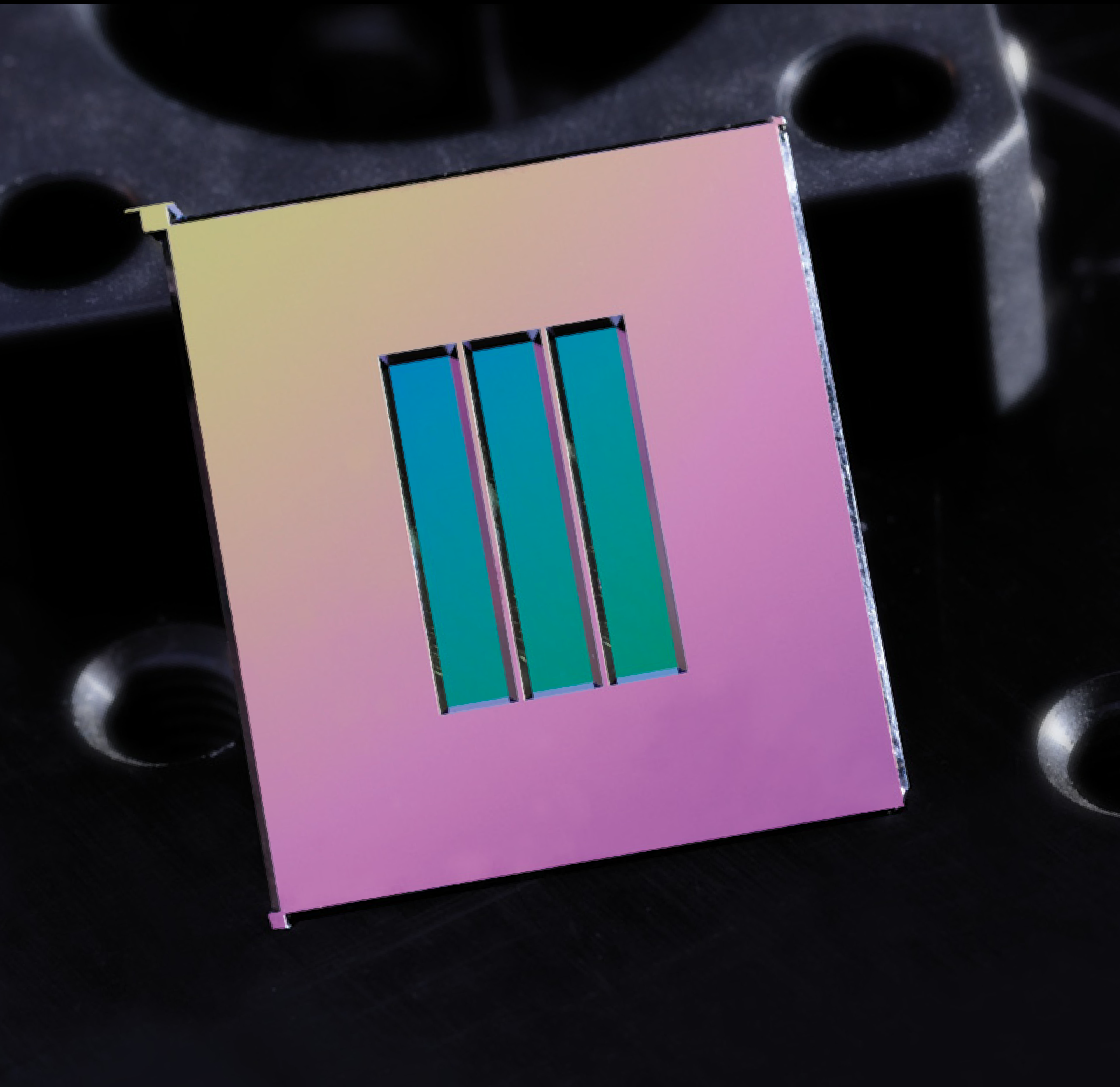


GaN MOS HEMT (metal –oxide-semiconductor high electron mobility transistor) developed for high temperature (>450 °C) operation and radiation hardness (2 Mrad).

GaN-based high-temperature and radiation-hard electronics

Data acquisition electronics and transmitters are the key electronics that must be operated in harsh planetary environments to condition signals from in situ sensors/detectors and transmit the sensor data to an orbiter or to Earth. Current data acquisition electronics and transmitter technologies require shielding from the harsh environments, which can add significant mass, power, and complexity to planetary instruments and can actually limit the functionality of the instruments. To address this issue, we develop novel GaN-based high-temperature and radiation-hard electronics that will enable data acquisition electronics and transmitters operating in harsh planetary environments. As a first step toward this goal, we have successfully developed GaN MOS HEMT (metal-oxide-semiconductor high electron mobility transistor) operating at > 450° C this year. Radiation testing based on TID (total ion dose) using a 60Co source at JPL indicates that the GaN MOS HEMTs have radiation tolerance of >2 Mrad. To the best of our knowledge, this is the highest operational temperature and radiation hardness reported for GaN FETs (field-effect transistors).

Using state-of-the-art microfabrication techniques, JPL has prepared perforated membrane beam splitters that meet specifications on surface flatness (RMS < 5 Å) in the VUV spectral region.



instruments

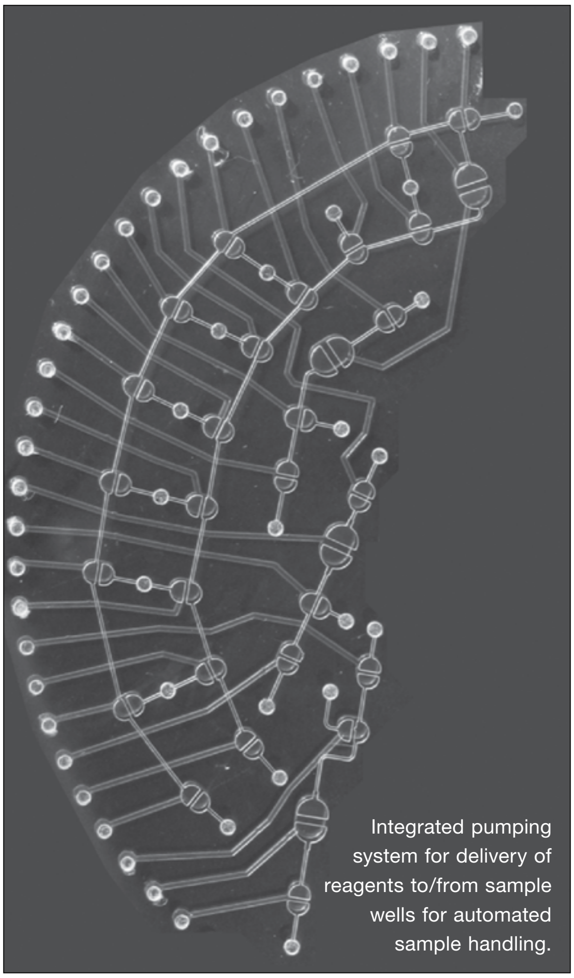
As planetary science has evolved from the successful observational missions of the 70s, 80s and 90s, increased emphasis has been placed on the exploration of nearby accessible planets. This has resulted in the development and deployment of new physical, chemical, and geological instruments on robotic platforms. In particular, the Mars Exploration Program has mature surface investigations that are currently searching for evidence of aqueous habitats and future missions will target the search for organic compounds. The ultimate goal of the program 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 the ambitious goals of the exploration phase of planetary science could be met by returning samples from Mars and other planetary bodies, for detailed analysis in terrestrial laboratories. The staggering cost of such sample return missions has led to the need to conduct careful analytical experiments remotely and robotically.

Questions of chemical composition, mineral structure determination, and the detection of trace compounds seriously challenge the instrumentation that must measure these properties in situ on the planet surface and in real time. In comparison to the characteristics of terrestrial laboratory instruments, the in situ equivalents are severely compromised by the mass and volume restrictions imposed by robotic platforms and long-distance remote operation. In response to this requirement for smaller and lighter instruments, MDL has embarked on a number of instrument developments using micromachining and semiconductor processing to bring to maturity novel chemical and physical instrumentation. These developments range 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. The following pages highlight MDL's microfluidic instrumentation and future developments in chemical, mineralogical, and optical components and systems. All of these developments leverage the core semiconductor-based processing tools of MDL including thin-film deposition, novel material growth, high-resolution lithography, controlled wet and dry etching, metallization, wafer bonding, and sophisticated analytical and structural characterization. These developments result from the strong scientific and technical collaboration of MDL investigators with our colleagues in academia as well as industry and other government laboratories.

instruments
lab-on-a-chip system development

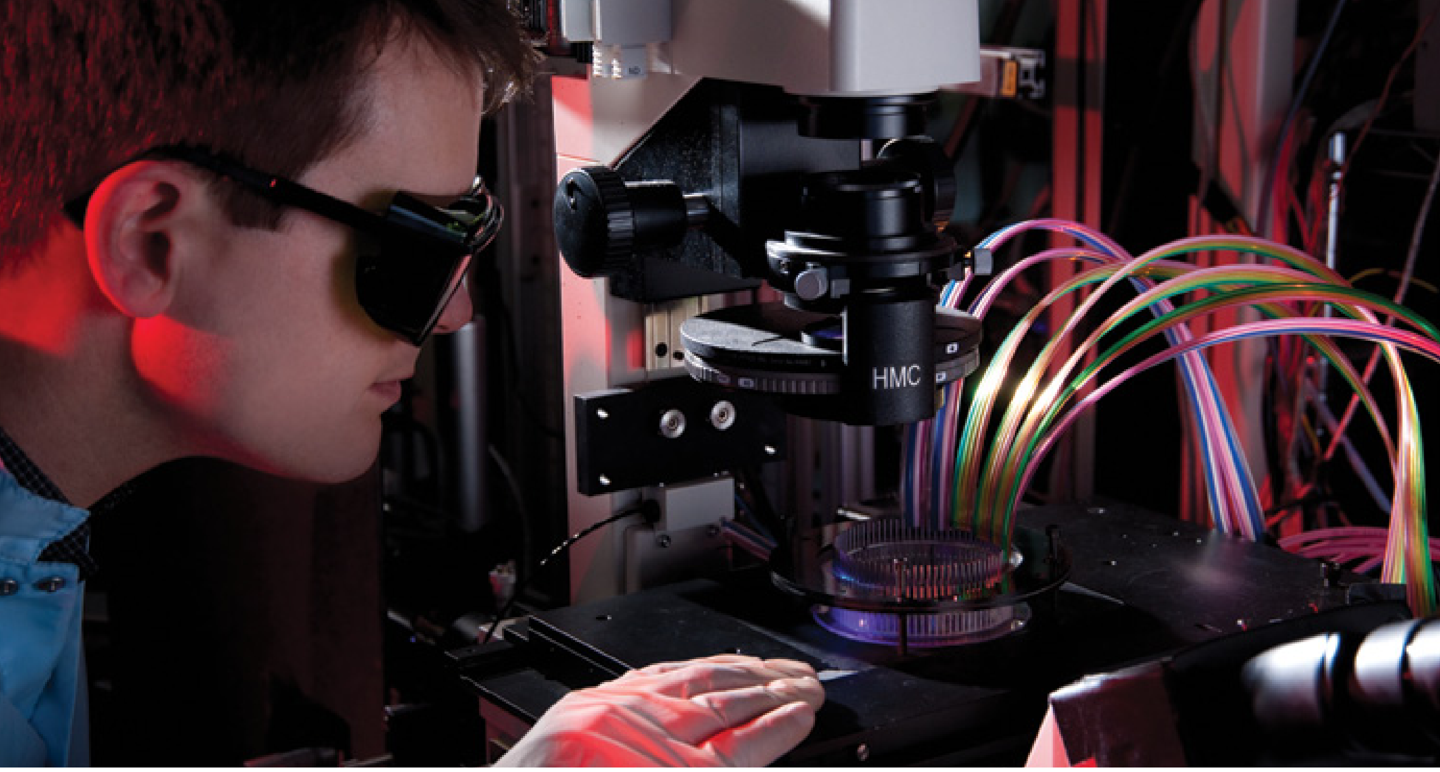
At the Microdevices Laboratory we are developing miniaturized "lab-on-a-chip" instruments for future landed missions to Mars, Titan, or icy solar system bodies. These instruments would be placed inside the payload of a future Mars rover or Titan lake lander, and would have the capability of analyzing liquid samples as small as a single drop for chemical traces of present life, past life, or evidence for chemical prebiological evolution. The high sensitivity of lab-on-a-chip systems, coupled with their low mass, volume, and power requirements, make them ideally suited for small-payload investigations of this kind. Over the past year, we have expanded our toolkit of lab-on-a-chip technologies in three key areas: microfluidic circuit development for automated sample handling, porous monolith polymerization for capillary electrochromatography application, and micromachined nozzle integration with lab-on-a-chip for nanoelectrospray ionization into a mass spectrometer system.

In 2009 we continued our ongoing efforts in the development of monolithic microfluidic valving and pumping systems, from a higher, system perspective, in which entire fluidic circuits were designed capable of performing all routing and mixing operations required by an autonomous lab-on-a-chip system. The figure to the right shows a photograph of one integrated circuit designed for coupling with microcapillary electrophoresis instrumentation intended for amino acid analyses aboard a Mars rover platform.

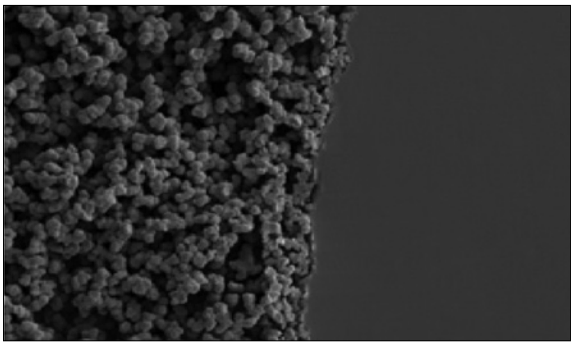


Integrated pumping system for delivery of reagents to/from sample wells for automated sample handling.

In collaboration with Fluigence and Los Gatos Research, we have begun photoinitiated polymerization of solid phase supports inside fluidic bearing microchannels in order to broaden the scope of analyses possible with our microfluidic instrumentation. Filling microchannels with porous polymer monoliths enables us to chromatographically separate entirely new classes of neutral molecular species, due to the differing strengths of interactions with this packing material as mixtures travel down the length of a microchannel. This separation technique, microcapillary electrochromatography, utilizes electric fields to drive fluid flows and is highly amenable to in situ flight system



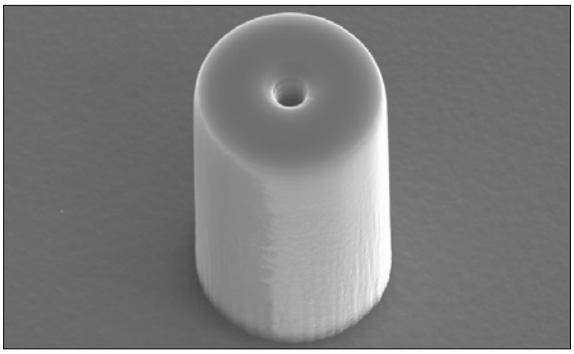
In collaboration with CorDiscovery, development has begun on an interface between MDL's glass microdevice wafer stacks and mass spectrometers, based upon the bonding of a micromachined silicon nozzle to the devices.



Scanning electron microscope images of microchannel cross-sections filled with porous polymer monoliths used as microcapillary electrochromatography columns on-chip.

implementation for extraterrestrial targets rich in neutral organic species. In this context, during the past year, we have initiated a new ASTID-funded program to apply this technique to the analysis of organic mixtures present on the surface of Saturn's largest moon, Titan.

In collaboration with CorDiscovery, development has begun on an interface between MDL's glass microdevice wafer stacks and mass spectrometers, based upon the bonding of an Advion micromachined silicon nozzle to the devices. Electrospray ionization mass spectrometry is essentially a universal detection technique, capable of detecting any ionizable species in solution, and therefore is an extremely powerful detection technique when coupled with on-chip chromatographic separations. Below is an electron microscope image of one such nozzle, having an inner diameter of 2.5 microns. The extremely small size of these orifices enables the creation of extremely stable, low-flow rate sprays from microchips into mass spectrometers, consisting of extremely fine droplets. Furthermore, the ultrasmall volume of these spray droplets drastically enhances the ionization efficiencies of target molecules (particularly in the presence of traces of salt samples) and reduces reagent consumption required for microanalyses on extraterrestrial targets.



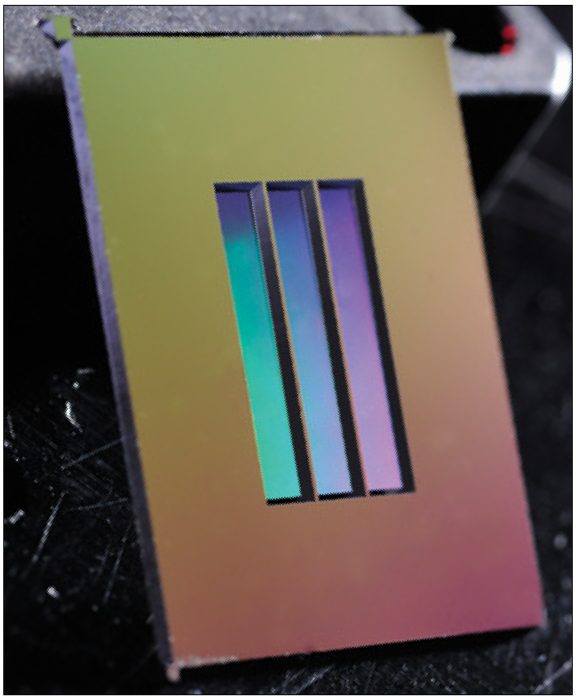
Scanning electron microscope image of a micromachined nozzle used for nanoelectrospray ionization mass spectrometry detection.

instruments
fourier transform x-ray (FTXR) spectral imager

Motivated by NASA's quest to identify chemical and organic biomarkers in minerals, we have initiated development of a novel, Fourier transform x-ray (FTXR) spectral imager in the soft x-ray region, capable of determining spatial distribution of oxidation state and bonding structure for significant elements. Features of (pre) biotic origin could be differentiated from abiotic features, and spectral fingerprinting of intracellular structures would be possible, important for biology and chemical investigations on Earth.

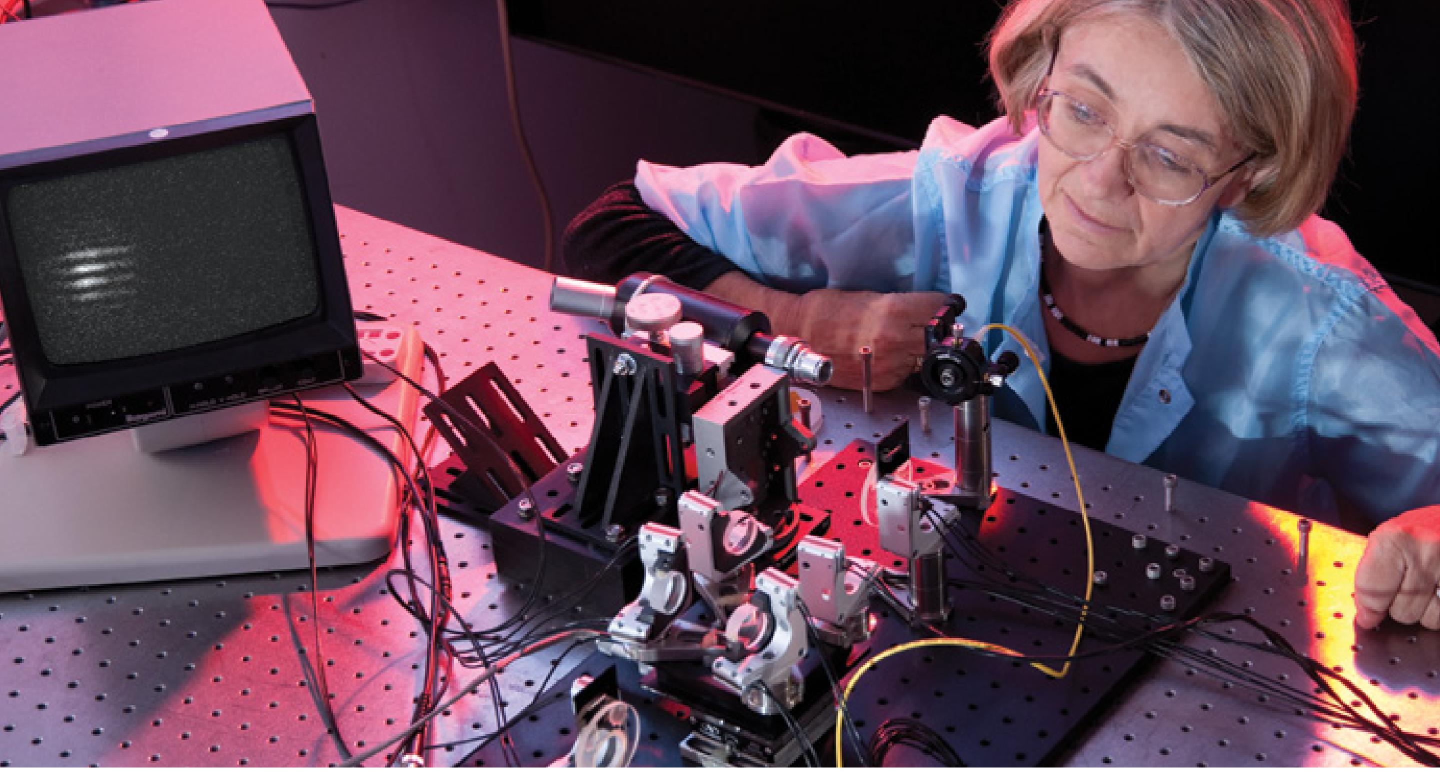
The FTXR concept relies on use of FT techniques similar to those in the IR to soft x-ray (100 eV to 500 eV) region, as a possible route for spectral imaging of bonding structure using a miniature instrument. The crux of the imager is an x-ray interferometer: the auxiliary subsystems include a miniature x-ray source, focusing optics, and a CCD-based detection system. When tuned over a range of path delays (frames), the FTXR interferometer sinusoidally modulates a spectrum of a wide-band source centered at the core wavelength of interest. The spectrum illuminates a target, the reflected signal is imaged onto a CCD, and the FT data acquired for different frames is converted in software, producing a spectral image per each pixel. The use of short wavelengths results in dramatic increase in spectral and spatial resolution over that for IR, the use of a miniature x-ray source and FT techniques results in efficient use of the beam spectral content, facilitating construction of a bench-top instrument.

The enabling component for the interferometer is beam-splitting mirrors. The mirrors are not available commercially. The multilayer approach used in the optical region is not applicable here, since it cannot meet requirements on mirror flatness and alignment

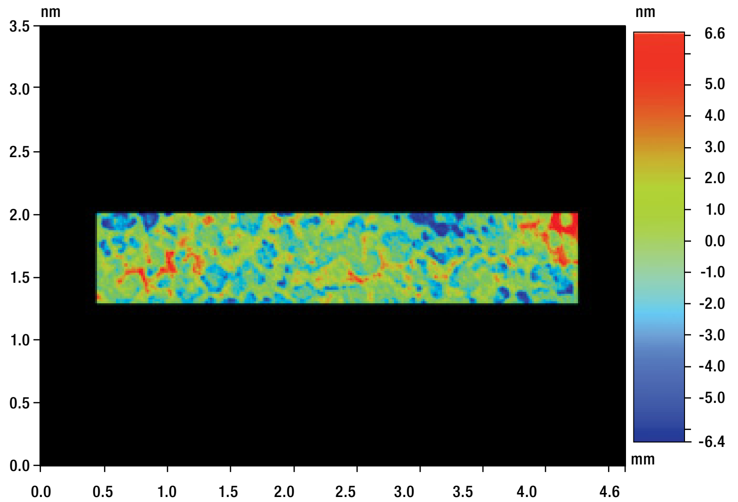


Beam-splitting mirrors consist of 200-nm-thick SiN films perforated with a large number of very small (3 mm x 15 mm) holes within a thick Si frame.

at shorter wavelengths. Precise control of surface planarity and roughness, much higher than in the IR region, are needed to achieve wave coherency required for high-contrast fringe forming (RMS < 5 Å at 120 eV, and proportionally less at higher x-ray beam energy). A new approach to beam splitter development is required. The approach pioneered at JPL uses thin SiN membranes perforated with a large number of very small holes. Using state-of-the-art microfabrication techniques that have only recently become available,



Using state-of-the-art microfabrication techniques...we have prepared membrane beam splitters that meet specifications on surface flatness in VUV spectral region (up to 100 eV) — something that has eluded other researchers for years...



FTXR spectral imager concept. The crux of the imager is an x-ray interferometer; the enabling component is an x-ray beam splitter.

Surface Statistics
Ra:1.34 nm
Rq: 1.68 nm
Rz: 11.35 nm
Rt: 12.99 nm

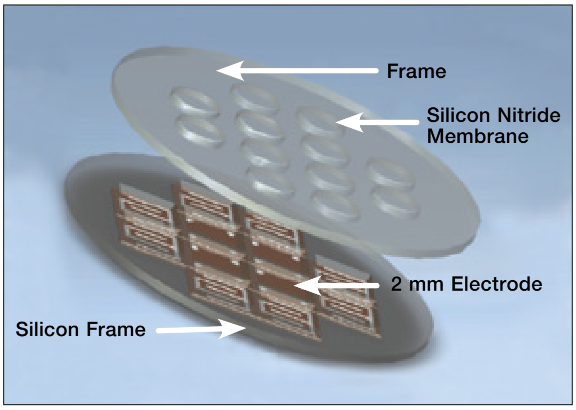
Set-up Parameters
Size: 640 x 480
Sampling: 7.26 μm

Mag: 1.4 X
Mode: PSI

we have prepared membrane beam splitters that meet specifications on surface flatness in the VUV spectral region (up to 100 eV) — something that has eluded other researchers for years — and incorporated them into a proof-of-concept Mach-Zehnder type interferometer. The microfabrication process is being further improved to meet higher specs to facilitate wave coherence at higher x-ray energy (up to 280 eV, carbon orbital line energy). A vacuum-compatible interferometer is being designed for fringe testing using the synchrotron source radiation at the Advanced Light Source (ALS), Lawrence Livermore Laboratory (LBL), UCB, at several beam energies. Plans are also being developed to perform fringe tracing within the interferometer test bed at the University of Uppsala using an He-discharge source at 40 eV.

instruments
in situ activation of microstructured biosensor arrays

Since our successful delivery of the first microfabricated chemical sensor array instrument developed to study the oxidation chemistry of the Martian surface (the Mars Oxidation Experiment named MOx) in 1996, we have been developing small and lightweight microinstruments based on thin-film sensors. Our interest is in chemical and biological sensor systems that emphasize reactivity and detection of chemical processes, including organic molecule decomposition. The sensor consists of a film of a specific compound and detecting transducer. The detector senses changes in the chemical properties of the film as the sensor is exposed to the reactants being analyzed. The MOx instrument used optical micromirror detection and our most recent instruments use chemiresistors. The chemical specificity of a sensing film can be quite high (responds to just a few reactants) but it is almost never absolutely unique. For unambiguous chemical species detection, an array of different sensors is used and their collective response is analyzed through combinatorial methods.

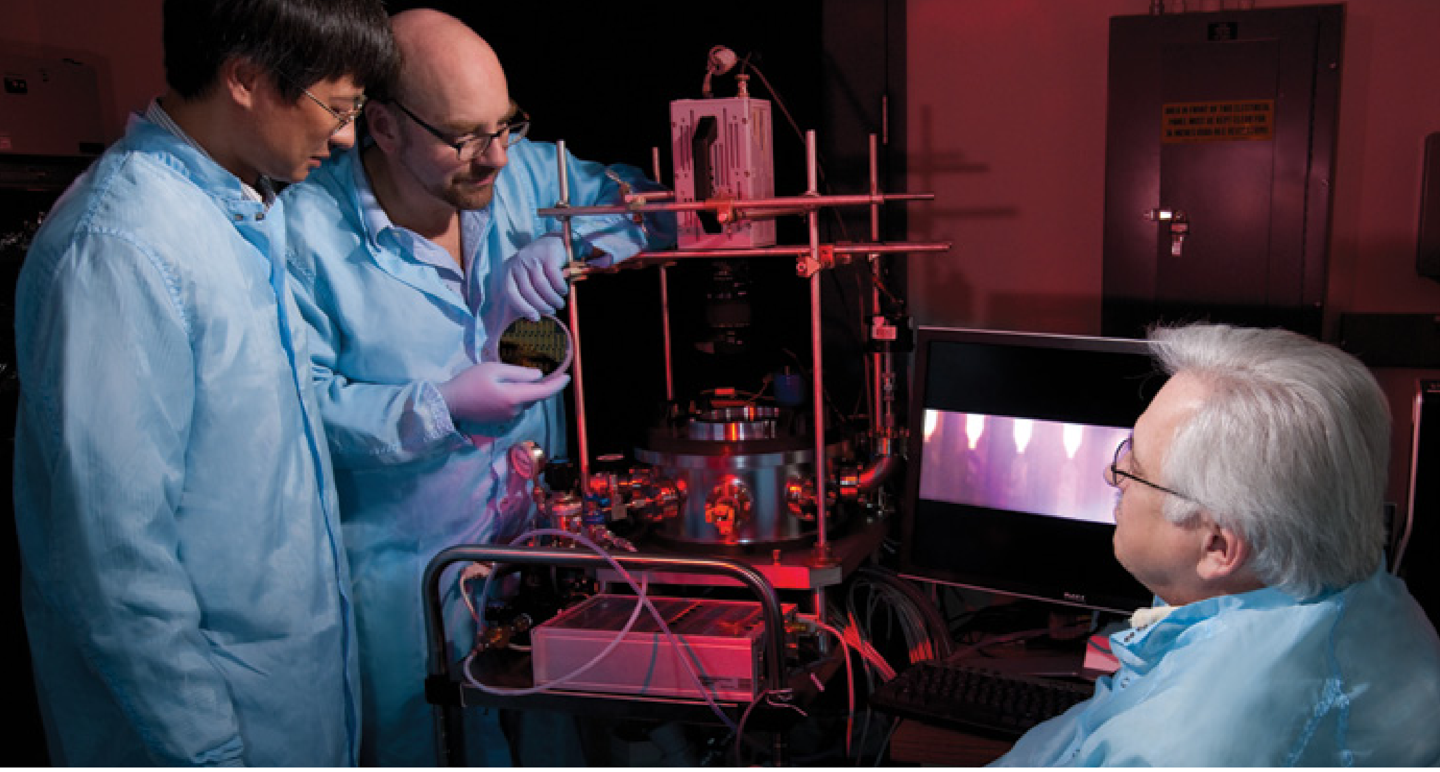


New approach that permits the deposition of reactive thin films within the sensor package directly before array deployment.

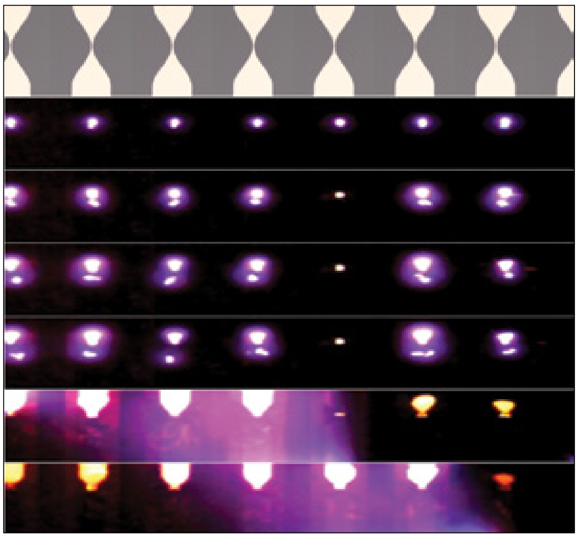
In our development of sensor films to follow the kinds of oxidative reactants that might be present on and in the Martian surface, we use a variety of metal films with different electromotive oxidation potentials. To characterize the chemical reactivity of the Martian environment, we must prepare the thin films in an extremely pure state and deliver them to the Martian surface in their unreacted condition. This required that we develop a hermetic sealing approach that would protect the film from atmospheric and contaminant exposure while on the Earth as well as during transit to Mars. Our solution to this sealing problem was the development of a thin silicon nitride membrane (150 nanometers thick) contained in an elemental silicon frame. Silicon nitride films are routinely fabricated in MDL in thicknesses from less than 10 to more than 1,000 nanometers. They are extremely robust and are impervious to gas leakage until purposely shattered.

During our development of the MOI (Mars Oxidant Instrument) component of the Urey package with NASA Ames and SETI, chemiresistor arrays were hermetically sealed with thin nitride windows. A small electrical trace was deposited on the top of the membrane and an ampherometric pulse was used to shatter the seal for deployment.

We also discovered that narrow metal traces could be heated to the point of flash evaporation without damaging the nitride, while heating wider traces led to the membrane decomposition. Based on these results, we have developed a new sensor approach for the deposition of reactive films inside the package just before the deployment of the array. The concept is illustrated on the left. The sensor package consists of a sensing array and a cover of a thin nitride membrane spaced 1 mm



Silicon nitride films are routinely fabricated in MDL in thicknesses from less than 10 to more than 1,000 nanometers. They are extremely robust and are essentially impervious to gas leakage until purposely shattered.



A typical deposition experiment.

above the measurement array. The underside of the nitride has a patterned metal trace covered with the chemical material that is evaporated onto the sensor electrodes. While the package is still sealed, this trace is rapidly heated, evaporating the overlaying film. After the deposition, a wider metal trace on the outside surface of the nitride is heated, rupturing the seal. This approach of using a thin hot-wire trace for in situ deposition eliminates a host of contamination problems while relieving much fabrication difficulty and reducing hermeticity requirements. This internal deposition can be used to deposit active biosensor films on top of evaporated metals for sensitive biomolecule detection.

Current work is using test arrays mounted in a controlled atmosphere chamber, applying electrical pulses while measuring the current profile, imaging the evaporation, monitoring the emission spectra, and following the composition and structure of the film.

A typical deposition experiment is shown on the left. The upper panel is an image of a 40-micron trace on the nitride. The other panels show video frames taken after applying the heating pulse. The upper four frames are the sequential video showing the trace for the first 0.5 milliseconds after the pulse trigger. The bottom two represent the 34th and 40th frames taken 3.4 and 4.0 ms after the pulse, showing the plasma triggered 1 ms after the event in the 25 torr N_2 atmosphere.

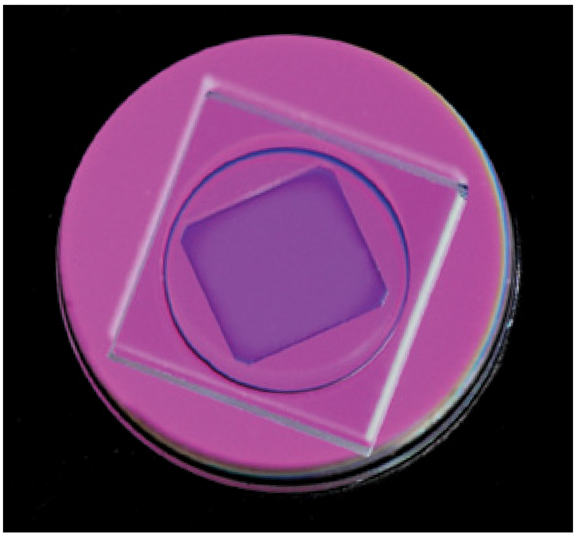
With this 10,000-video-frame-per-second imaging capability together with the electrical and spectral time profiles, we are determining the optimal geometry and power sequence to control the formation of metal, semiconductor, and organic films for this next generation of in situ deposited thin film sensor arrays.

instruments
raman spectrometers

When a monochromatic light is incident on a sample, some of the light is transmitted, some is absorbed, and some is scattered. Most of the scattered light has the same wavelength as the incident light. However, a small fraction of the scattered light is shifted in wavelength by the vibration and rotations of molecules in the sample. This shift in spectra is indicative of the vibrational modes of the bonds excited within the sample, and can thereby be used to identify the molecules present. Since no sample preparation is required, Raman spectroscopy is a practical and powerful analytical tool for planetary missions. Refer to the book entitled *Analytical Applications of Raman Spectroscopy* edited by Michael Pelletier for an excellent overview of the field.

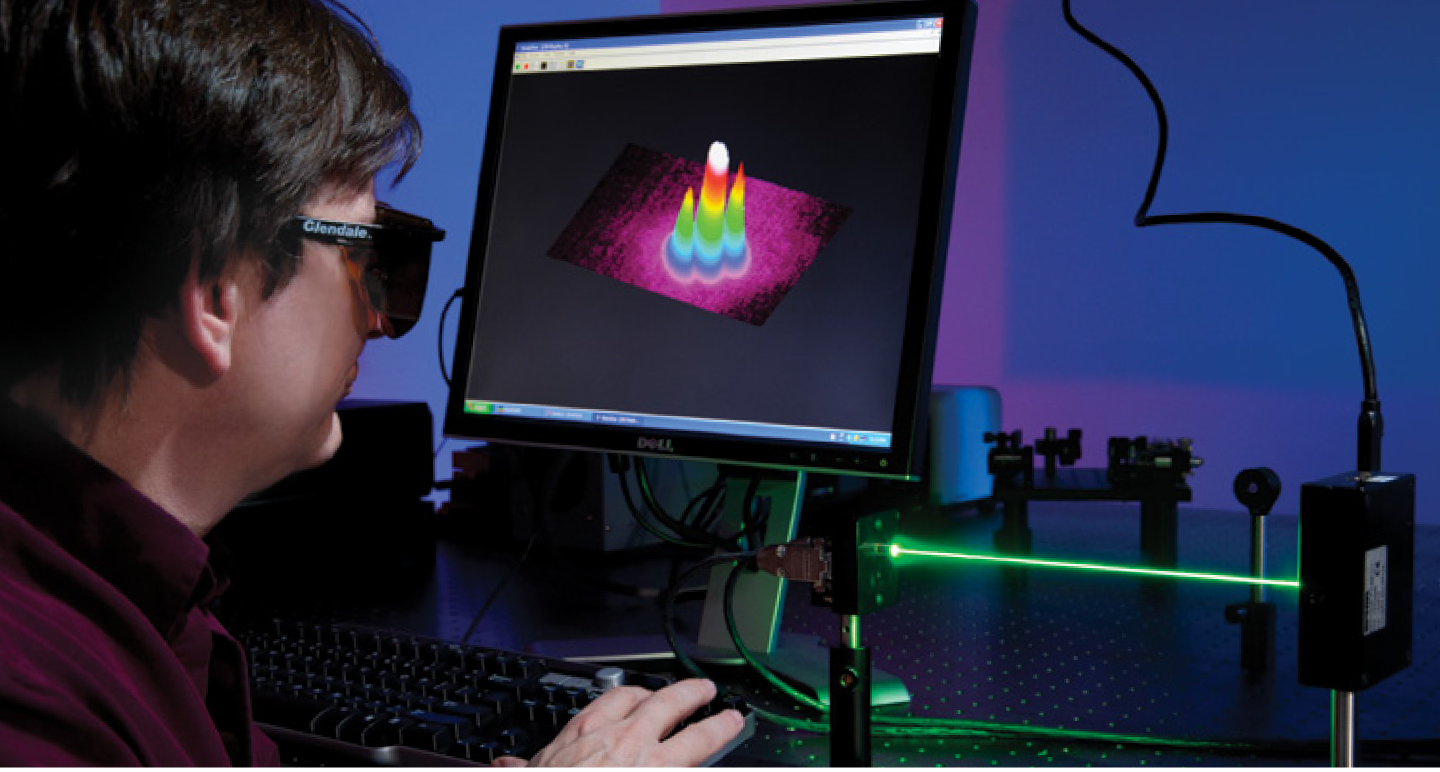
Planetary scientists at JPL and other laboratories are developing Raman spectrometers that are capable of analyzing rocks and surfaces with mixed mineral composition. A design under consideration at JPL uses a Raman probe-head to focus laser light onto individual mineral domains as the probe is automatically scanned across the sample's surface. During the scan, individual minerals are indentified and a histogram is tabulated using a technique called point counting to provide a quantitative analysis of the sample's mineral composition.

The laser used in the Raman probe-head is a critical component of the instrument since it is required to provide an optical output beam that is both wavelength stabilized and spectrally narrow with a spatial beam profile that enables it to be focused down to a nearly diffraction-limited spot in order to optically interrogate the mineral domains individually. For many planetary geology applications, green lasers are often employed because they induce enough Raman scattered light for darker minerals using modest amounts of power. Green



This microchip laser can be end-pumped by an 808 nm laser directly or via a fiber to provide the 532 nm wavelength light needed for a planetary Raman spectrometer.

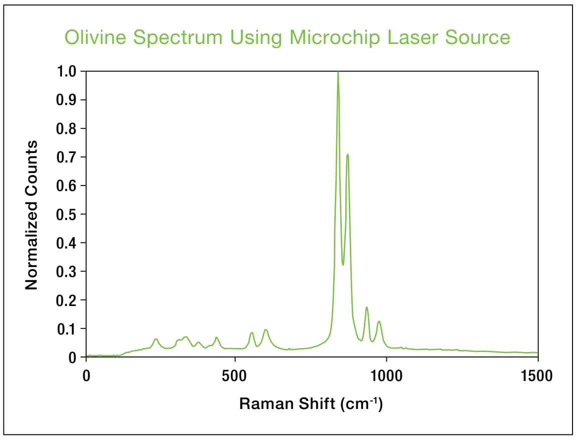
lasers capable of producing light of the quality and robustness needed for Raman spectroscopy are solid-state. With the exception of semiconductor lasers, the gain media of solid state lasers are electrical insulators, and hence are most appropriately optically pumped to produce gain. Diode-pumped solid-state (DPSS) lasers use a semiconductor diode to directionally pump a host crystal from the end or from the side. The host crystal is typically doped with a rare earth element because the excited states of rare earth ions are not strongly coupled with the thermal vibrations of the crystalline lattice and therefore lasing can be achieved using relatively low pump powers. While a great variety of DPSS lasers have been developed, neodymium-doped YAG or Nd^{3+}:YVO_4 are by far the most common. When pumped at a wave-



Planetary scientists at JPL and other laboratories are developing Raman spectrometers that are capable of analyzing rocks and surfaces with mixed mineral composition.

length of 808 nm with a semiconductor laser, both types of crystals produce light at a wavelength of 1064 nm with nearly 50% conversion efficiency. For CW Raman applications, the 1064 nm light is frequency doubled using an intercavity KTP (potassium titanyl phosphate) crystal to produce a green, 532 nm output beam.

DPSS lasers suitable for a planetary Raman instrument could be implemented as small, open-cavity or monolithic cavity lasers nominally 25 mm or less in length. Alternatively, very small (<1.5 mm cavity, 3 mm diameter) DPSS microchip lasers could be employed. The larger cavity designs tend to expose the coatings on the host crystal to lower power densities than the much smaller microchip lasers but may be less mechanically robust. However, microchip lasers incorporate flat-flat resonator design using thin-film mirror coatings, requiring the thermal lens produced by the host crystal to stabilize the laser cavity. At MDL, we are evaluating the trade-offs between size, performance, and reliability in both of these DPSS laser architectures. Free space and microchip DPSS lasers are being evaluated from a variety of vendors in order to arrive at a DPSS laser design that will produce a spatially and spectrally well-behaved output beam over the temperature extremes encountered during planetary missions to Mars and perhaps other venues.



Raman spectrum of a peridotitic olivine (fosterite) acquired using a Raman spectrometer with a VLOK microchip laser integrated within a Raman probe-head. The microchip was end-pumped with 808-nm-wavelength light supplied from a multimode optical fiber.

This year, both free space and microchip architectures have been characterized under a variety of different operating conditions and temperatures. Final evaluation of the DPSS lasers is being performed by incorporating them into a Raman probe-head and using them to acquire Raman spectra of known mineral standards and evaluating the quality of the spectra observed.

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2. D. Z.-Y. Ting, C. J. Hill, A. Soibel, S. A. Keo, J. M. Mumolo, J. Nguyen, and S. D. Gunapala, "A High-Performance Long Wavelength Superlattice Complementary Barrier Infrared Detector," *Applied Physics Letters,* vol. 95(2), p. 023508, 2009.

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4. C. J. Hill, A. Soibel, D. Z.-Y. Ting, S. A. Keo, J. M. Mumolo, J. Nguyen, M. Lee, and S. D. Gunapala, "High-Temperature Operation of Long-Wavelength Infrared Superlattice Detector with Suppressed Dark Current," *Electronics Letters,* vol. 45(21) p.1089, 2009.

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1. "Piezoelectrically Enhanced Photocathode," S. Nikzad, R. Beach, R. Strittmatter, L. D. Bell, US Patent #7,592,747.

2. "Methods for Growing a Back Surface Contact on an Imaging Detector Used in Conjunction with Back Illuminated," M. E. Hoenk, J. Blacksberg, T. J. Jones, and S. Nikzad, patent filed.

3. "Methods to Improve Indium Bump Bonding via Indium Oxide Removal Using a Multistep Plasma Process," F. Greer, M. R. Dickie, T. J. Jones, T. J. Cunningham, E. R. Blazejewski, S. Nikzad, and M. Hoenk, provisional patent filed.

4. "Delta-Doping at Wafer Level for High-Throughput, High-Yield Fabrication of Silicon Imaging Arrays," M. Hoenk, F. Greer, and S. Nikzad, provisional patent filed.

5. "Ultra-Compact Spectrometer Apparatus and Method Using Photonics Crystals," D. Z. Ting, C. J. Hill, S. Gunapala, and S. Bandara, U.S. Patent #7,599,061,B1.

6. "Anti-Reflective Device Having an Anti-Reflection Surface Formed of Silicon Spikes with Nano-Tips," Y. Bae, S. Mobasser, H. Manohara, and C. Lee, U.S Patent #7,595,477, Issued: 9/9/2009.

hosting, chairmanships, and other MDL efforts

1. Lloyd Doug Bell, a Senior Research Scientist, organized and co-chaired the Materials Research Society's symposium on "Compound Semiconductors for Energy Applications and Environmental Sustainability." He also co-edited the proceedings of the symposium MRS VOL 1167, editors: F. Shahedipour-Sandvik, E. Fred Schubert, L. Douglas Bell, Vinayak Tilak, and Andreas W. Bett.

2. Shouleh Nikzad co-organized the annual meeting on International Brain Mapping and was the associate editor on the NeuroImage special issue. She is invited to continue on the editorial board.

3. Michael Hoenk (389H and affiliate of the Advanced Detectors Group) is invited to the program committee of the SPIE Detectors and Focal Planes in the Optics and Photonics Conference.

4. The Infrared Photonics Technology Group (S. D. Gunapala, D. Z. Ting, C. J. Hill, A. Soibel, J. K. Liu, J. M. Mumolo, S. A. Keo, and J. Nguyen) organized and hosted the Quantum Structure Infrared Photoetector 2009 International Conference (QSIP 2009), January 18–23, 2009, in Yosemite, California.

5. A. Kleinsasser chaired the U.S. Workshop on Superconductor Electronics, held in Warner Springs, CA, on October 25–29, 2009. George Kerber served as local chair. This invitation-only biennial meeting has provided, since 1978, a unique forum for superconductor electronics researchers in U.S. institutions to meet for open and frank technical discussions. This year's workshop, attended by approximately 60 professionals and students, covered low-energy computing, signal processing, and mK digital readout for sensors and qubits.

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)
- Plasma Enhanced Chemical Vapor Depostion (PECVD) Systems for Doped and Undoped Amorphous Silicon (2)
- 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 (9)
- Critical Point Dryer
- Rapid Thermal Processors/Contact Alloyers (2)
- Polishing and Planarization Stations (5)
- Strasbaugh 6EC Chemical Mechanical Polisher

packaging

- 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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