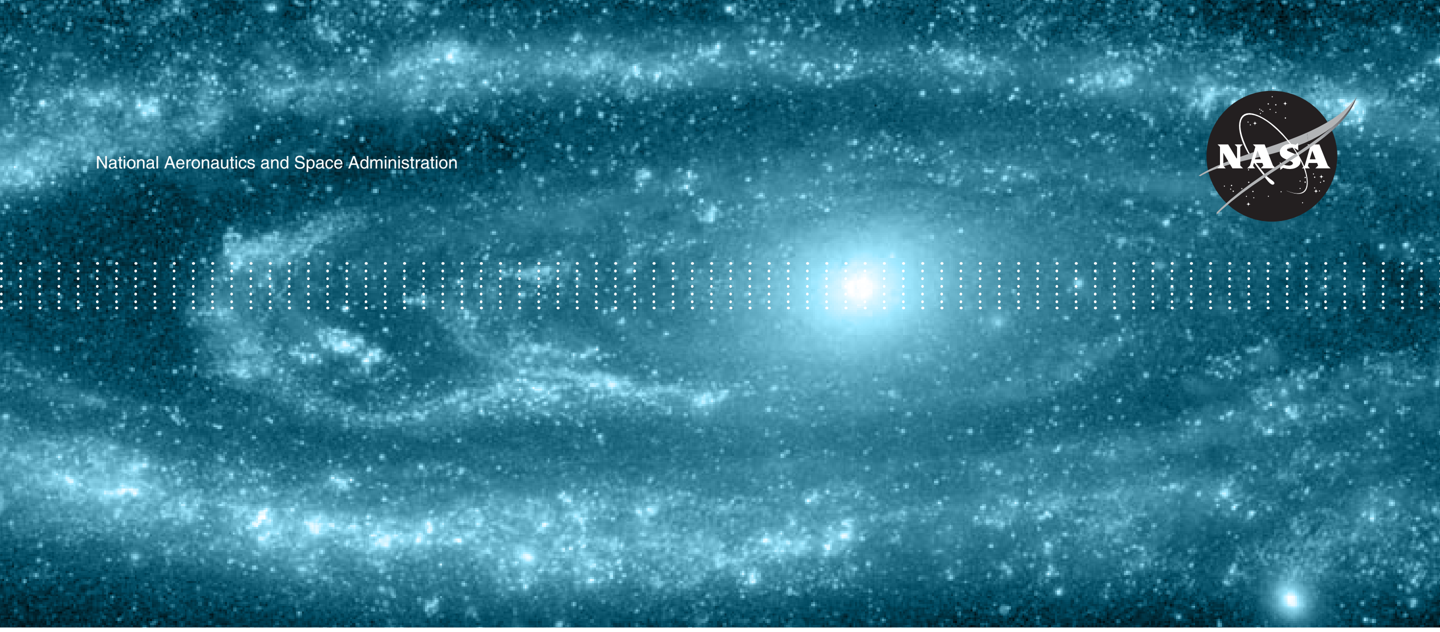
National Aeronautics and Space Administration



MDL 07 ANNUAL REPORT

Microdevices Laboratory

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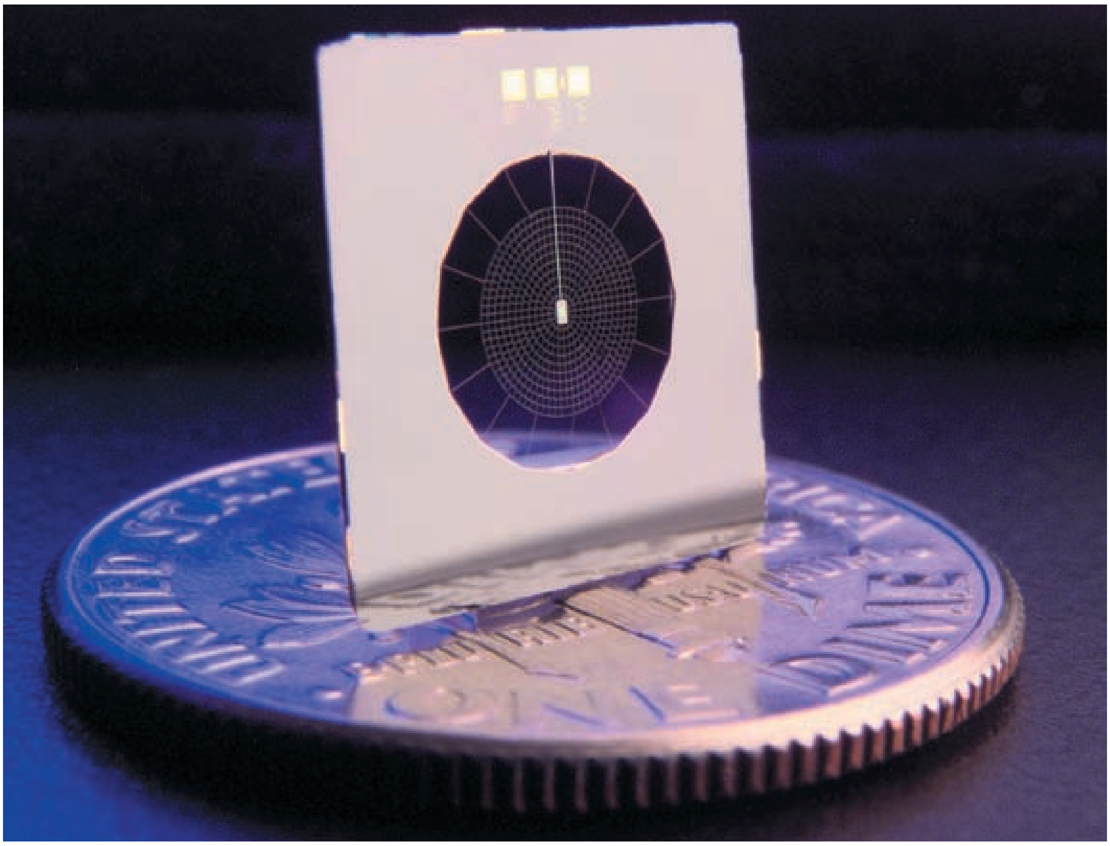
{Director's Letter}

As is true for JPL as a whole, our goals at MDL are not modest. We aim to harness the enormously powerful and rapidly advancing techniques and tools for micro-and nanofabrication, in order to develop innovative new devices and technologies that enable JPL and NASA to carry out new missions, to perform new measurements, and ultimately to expand the frontiers of science. It is enormously exciting to be able to start with a good idea and to have a chance of enabling a project that will make a large impact, whether it involves learning about the physics of the universe when it was only 10^{-32} seconds old, characterizing molecular species and their chemistry in Earth's atmosphere, or searching for signs of past or present life on Mars. Our task is not easy: taking a technology from zero to space flight takes time, money, perseverance, and above all, patience. A good recent example is the development of efficient, low-power infrared lasers for the Tunable Laser Spectrometer instrument for the Mars Science Laboratory rover, an achievement that was highlighted by the 2006 Ed Stone Award for Outstanding Research Publication to Rui Yang. And while we certainly do not succeed with all of the ideas that we attempt, nor do we expect to, it is remarkable to me how often we do succeed. I hope you will agree after reading this Report.

On October 27, 2008, MDL will be celebrating its 20th anniversary. Two decades is a long time in the fast-moving world of microtechnology, so this anniversary represents an appropriate moment to reflect on MDL's history, its status today, and its future.

In his speech during the dedication ceremony in October 1988, JPL Director Lew Allen explained MDL's genesis: "Just a little over five years ago, NASA, meeting with members of the Caltech Board of Trustees, requested that JPL consider establishing a center of excellence in space microelectronics." Indeed, this request came in July 1983 during a meeting of the Trustees' JPL committee in Washington D.C., from Burton Edelson, who had been appointed as NASA's Associate Administrator for Space Sciences just a year earlier. Edelson's proposal was actually a response to a letter from Mary Scranton, the chair of the Trustees' JPL committee, asking Edelson whether there were new areas, other than robotic exploration, in which JPL could take on the lead responsibility for NASA.

Although initially he may have been somewhat skeptical, Lew Allen became a strong supporter of the concept and delegated the task of organizing a new microelectronics program to Terry Cole, who was JPL's Chief Technologist at the time. Cole identified several initial research areas: photon detectors, especially for infrared and submillimeter wavelengths; solid-state lasers; neural networks and custom microcircuits; and parallel computation. The basic idea was to build the new program on a base of activities that were already underway at JPL and Caltech, such as John Hopfield's work on neural networks and Geoffrey Fox and Charles Seitz' work on "hypercube" concurrent computation. Cole's initial program represented a combination of projects that would be done both at the materials and device level, such as detectors and lasers, and at the system level, such as parallel computation. Device development required a new cleanroom with sophisticated processing equipment, so plans for the MDL facility were generated. By January 1987,



Spiderweb bolometers designed and fabricated at MDL. These bolometers can detect very small amounts of energy and convert them to electrical signals. They are currently the most sensitive direct detectors for light in the far-infrared to millimeter wavelength range.

the Center for Space Microelectronics Technology (CSMT) had been established with Carl Kukkonen serving as its Director, and construction of the new NASA-funded MDL building was started. With the recruitment of new staff, acquisition and installation of the new device-processing equipment, and completion of the building, the MDL was in full operation by 1990. Many of the MDL activities that you will read about in the following pages can trace their origins to the original program that Cole and Kukkonen put together.

Let's fast-forward to 2007, a year that held a number of positive developments for the MDL. This 2007 Annual Report is actually the first time that MDL has produced such a publication. In this Report, you can read about the contributions to JPL and NASA that MDL has made and is continuing to make. Throughout the 1990s, MDL's work had been reported under the CSMT umbrella in an annual publication entitled *Space Microelectronics*, but that publication and CSMT itself disappeared as a result of management restructuring. Of course, MDL continued operating, but its management had been decentralized and its groups were split across several sections at JPL. This was reversed in 2007: I started my assignment in the new position of MDL Director with Siamak Forouhar as my deputy, and the core MDL groups were integrated into a single section under the management of Marty Herman and Elizabeth Kolawa, as part of the overall reorganization of the Instruments and Science Data Systems Division led by Tom Luchik. In addition to these organizational changes, the MDL facility has enjoyed a number of upgrades in 2007, both large and small. A significant investment in new processing equipment was made, as is described in more detail in the next section of the Report. The lobby of the MDL building has been remodeled, and a large mural depicting MDL's numerous contributions has been installed. Please come have a look!

The future holds significant challenges, as dictated by our ambitions. With the management reorganization accomplished and the renewal of the equipment and facilities in progress, it is time to pay attention to MDL's scientific staff. While we are fortunate to have exceptionally talented scientists working at the MDL, a significant portion of the staff came to JPL in the start-up phase around 1990, and as can be expected, there has been significant attrition since then. It is time to make a concerted effort to recruit top-notch researchers to MDL, who will exploit our outstanding facilities to develop new programs and thrusts, and who will stimulate the existing staff and hopefully develop collaborations with them. We have started a new MDL seminar series, inviting speakers from both outside and inside JPL to tell us about new missions and their science goals, new micro-and nanotechnologies under development, or even the nitty-gritty details of device processing. We are also planning to invite a Visiting Committee to come to MDL in 2008. The Committee will hear presentations about the work being done here and will have in-depth individual discussions with our staff. We will ask the Committee for their opinions and recommendations on how we might improve.

In closing, let me say that it is a distinct privilege to be able to work with the excellent scientists at JPL and MDL on some very exciting projects, and to have access to the wonderful facilities here. In return, my hope is to be able to contribute in some small way to JPL's success.

Jonas Zmuidzinas
Director, JPL Microdevices Laboratory

{Chief Technologist's Statement}

Under the leadership of JPL Director Dr. Lew Allen, the JPL Microdevices Laboratory (MDL) was established in October 1989 as an integral component of the Center for Space Microelectronics Technology (CSMT) program office. Since then, MDL has provided end-to-end capabilities in support of design, fabrication, and characterization of advanced components and sensors. Research and development in MDL have made seminal contributions to the national and international revolution in the technology of microdevices.

Today, MDL and its products provide novel and unique components and subsystems responsible for advances that have enabled remarkable achievements in space and many other applications, in support of NASA's mission and other national priorities.

Under the leadership of Prof. Jonas Zmuidzinas, who was recently named Director of MDL, and owing to the work and contributions of the talented MDL scientists, technologists, and research staff, developments in novel detectors are in progress. These hold the promise of further extensions of our ability to peer into the far reaches of our solar system, our own and other galaxies, and the very beginnings of our universe.

Paul Dimotakis

Paul E. Dimotakis
JPL Chief Technologist

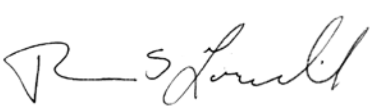
{Division Manager's Statement}

During the last few years, JPL has made significant investments in its Microdevices Laboratory (MDL), expanding its breadth and capability, and enhancing its continued tradition of innovative microdevice and nanotechnologies. This investment enables leading-edge *in situ* planetary-science as well as remote-sensing technologies targeting astrophysics, planetary and Earth science observations that comprise the prime JPL mission.

This year, Professor Jonas Zmuidzinas accepted the position of Director of the JPL Microdevices Laboratory, adding an important element in the programmatic guidance of MDL. A recent reorganization has also brought scientists and technologists relying on MDL into a single organization, the Instruments and Science Data Systems Division. Working with Prof. Zmuidzinas, we identified several upgrades that were implemented in FY2007, with plans in place for additional future capability upgrades.

As the JPL MDL enters its 20th year of operation, we look forward with high expectation for continued innovation and invention in our microdevice and nanotechnologies that will enable a continuation of JPL's record of unprecedented discovery in pursuit of its prime mission and its unique contributions to various projects of national interest.

As you will read in this Report, it has been a busy and productive year for the MDL. I am looking forward to the continuation of JPL's development of new technologies that will bring tomorrow what we can only imagine today.



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

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The Microdevices Laboratory: Infrastructure and Capabilities

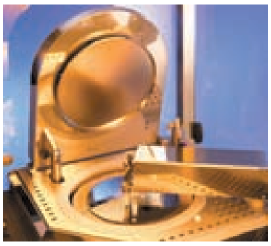
Microdevice fabrication requires sophisticated equipment for the deposition, etching, and patterning of device layers, and must generally be done in a very clean environment to avoid defects and contamination. As a result, it is highly desirable to co-locate such activities, to allow expensive equipment to be shared, and to spread the maintenance burden over a larger base of activity. JPL is fortunate to have an excellent facility, the Microdevices Laboratory, which was constructed in the late 1980s and is located in building 302 at JPL. The heart of MDL is a 13,000-square-foot cleanroom that is used by over 70 research scientists.

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 MDL cleanroom is divided into various zones according to cleanliness standards, ranging from class 100,000 for the rooms housing epitaxial deposition systems, to class 10 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.

Continuous investment in MDL's processing equipment is essential. The equipment for micro- and nanofabrication 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 projection lithography system capable of 0.25-µm resolution. However, because the MDL


Left: UHV Sputtering Systems for deposition of high-quality metals and dielectrics. Right: Newly purchased ultra-high-vacuum (UHV) electron beam for metal evaporation.

Microlithography 4 Module Cluster Cassette-to-Cassette Spin/ Developer system.

Photolithography area.

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 details on MDL's equipment complement may be found in Appendix A.

2007 Highlights

Driven primarily by the need to produce large detector arrays, a major theme for MDL equipment upgrades for the past several years has been to develop the capability for processing 150-mm (6-inch) diameter wafers, instead of the 75-mm or 100-mm-diameter wafers now in typical use. Several new 6-inch-capable systems were installed and brought into operation in 2007, including systems for the deposition of metal and dielectric films by UHV sputtering, and a system for low-pressure chemical vapor deposition (LPCVD). The LPCVD technique may be used to grow a variety of films at relatively high temperatures, such as low-stress silicon nitride. In addition, a carbon nanotube furnace and a xenon difluoride (XeF_2) etcher were installed in 2007. Finally, MDL's primary photolithography system, the Canon EX3, was upgraded by adding a new reticle library.

A number of equipment items providing enhanced capabilities were specified and purchased in 2007, and will be installed in 2008:

1. AUTOMATED PRECISION PHOTORESIST PROCESSING of 75-mm (3-inch) to 200-mm (8-inch) diameter wafers [SUSS MicroTech Inc., Gamma Microlithography 4 Module Cluster Cassette-to-Cassette Spin/Developer].

2. INDUCTIVELY COUPLED PLASMA-ENHANCED CHEMICAL VAPOR DEPOSITION (ICP-PECVD) for the deposition of a variety of high-quality dielectric films at relatively low temperatures [Oxford Instruments, Plasmalab System 100 Advanced ICP 380 HD PECVD].

3. atomic layer deposition (ALD) for producing extremely thin, uniform, conformally-coating films [Oxford Instruments, Plasmalab 80 OpAL].

4. inductively coupled plasma reactive ion etching (ICP-RIE) for III-V compound semiconductor devices [Oxford Instruments Phoenix ICP Chlorine RIE].

5. electron-beam evaporator dedicated for III-V compound semiconductor devices [Temescal BJD / FC-2000].

6. indium evaporator for large wafer bump-bonding [Denton Infinity 22].

7. semiconductor parameter analyzer [HP Agilent 4155c].

8. wet bench for RCA cleaning of 150-mm (6-inch) diameter wafers, with rinser-dryer.

9. 150-mm (6-inch) capability upgrade for superconductor sputtering system.

10. subkelvin, high-throughput cryogenic test facility for superconducting materials and device testing.

11. proximity correction software for MDL's JEOL JBX-9300FS electron-beam lithography system [GenISys Layout BEAMER].

In addition to the equipment investments, several facility upgrades were undertaken. These include providing better humidity control in the cleanrooms, which is necessary for reproducible photolithography; providing increased lighting levels of the lab; replacement of the roof; installation of a 50-kW photovoltaic system; replacement of the security monitoring system; and replacement of the obsolete toxic gas monitoring system. Looking ahead, a design was completed for upgrading the system that provides cooling water to the process equipment.

Left: Electron-beam lithography system. Right: MDL's toxic gas monitoring system was replaced in 2007 with a new Honeywell Analytics Zellweger Vertex 72 System.

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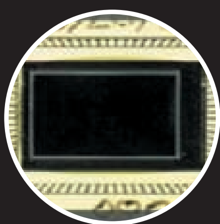
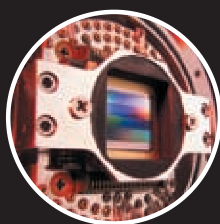
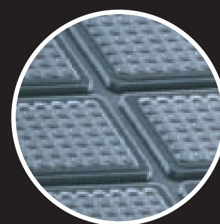
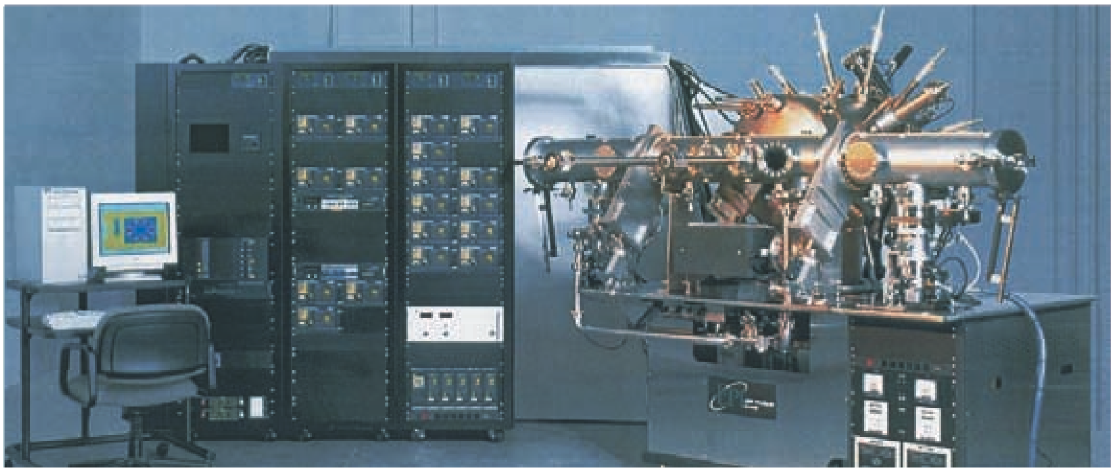
Infrared Detectors Using Engineered Compound Semiconductors

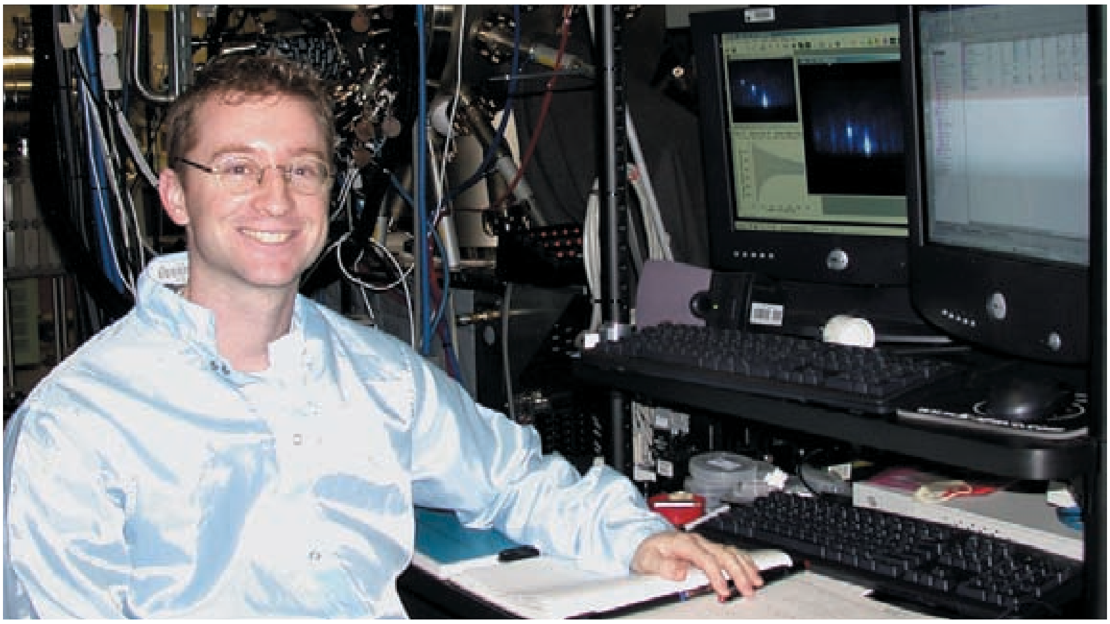


Microscope photograph of two polarized QWIP pixels. The reflection grating polarizers are oriented diagonally (left) and horizontally (right).

Of the many remarkable fabrication techniques in daily use at the MDL, molecular-beam epitaxy, or MBE, is perhaps the most amazing. Invented in the late 1960s by Alfred Cho at Bell Laboratories, MBE allows the growth of crystalline samples with extremely precise control, so that structures can be built up a single atomic layer at a time. The MBE technique is applicable to a wide variety of compound semiconductors (those composed of elements from rows III and V in the periodic table, or II-VI) including binary and ternary materials such as GaAs, $Al_xGa_{1-x}As$, $In_xGa_{1-x}As$, $Ga_xIn_{1-x}Sb$, InAs, etc. This flexibility, along with atomic layer control, allows MBE production of semiconductor materials that are precisely tailored and optimized to match demanding application requirements—a method often called "bandgap engineering." Furthermore, these exotic layered materials can often be grown on industry-standard wafers such as GaAs that are available in large sizes and at low cost. One of the major application areas being pursued at MDL is the use of these materials for infrared detection. At present, most infrared detectors rely on a bulk semiconductor such as $Hg_xCd_{1-x}Te$ that has an electron bandgap small enough to allow the absorption of low-energy infrared photons. While excellent performance can be obtained, issues and problems persist, such as detector uniformity, maximum wavelength, maximum array size, manufacturing yield, and especially cost. These factors continue to motivate the work being done at MDL. Furthermore, while sensitive far-infrared detector arrays are badly needed for future astrophysics missions such as SAFIR, the production of large arrays for wavelengths beyond 30 μm remains a long-standing problem. A new device concept currently under development, called QWISP, may provide a solution.



MDL's MBE system for compound semiconductors.



MDL scientist Cory Hill, master of MDL's III-V MBE system.

Current Projects

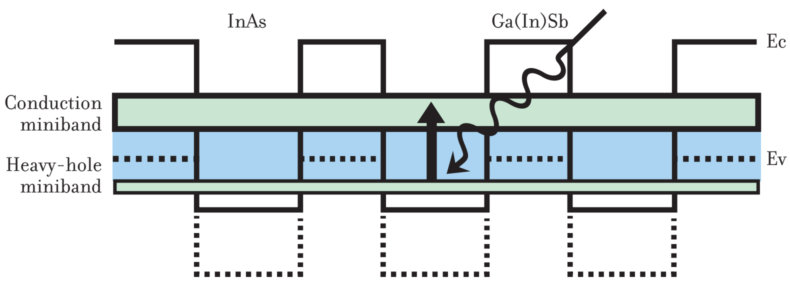
1. QUANTUM-WELL INFRARED PHOTODETECTORS (QWIPS): QWIPs were proposed and developed starting in the early 1980s. The concept is straightforward: electrons are trapped in a shallow potential well — the quantum well — created by bandgap engineering, but may escape the well by absorbing infrared photons, thereby becoming mobile carriers of electrical current. Work at MDL is focused on producing large-format arrays in the 1–16 megapixel range, and on integrating additional functionality, such as multicolor operation or polarization sensitivity. The III-V materials growth and processing technology used to produce QWIPs is relatively mature. As a result, these arrays show extremely high pixel-to-pixel uniformity, high pixel operability, and low 1/f noise as compared with II-VI bulk semiconductor sensors such as HgCdTe. Often pixel-to-pixel non-uniformity is the most dominant noise component in large-format imaging arrays; thus, a QWIP can meet <15 mK thermal sensitivity for many terrestrial imaging applications due to its high uniformity.

2. SUPERLATTICE INFRARED DETECTORS: Superlattices are engineered periodic structures made of alternating material layers, usually grown by MBE. Although the use of "type II" GaInSb/GaSb superlattices for infrared detection was proposed 20 years ago by Christian Mailhiot and Darryl Smith (who worked together at Caltech in the mid-1980s), there has been a recent resurgence of interest in these devices. Mailhiot and Smith predicted that the performance of properly designed superlattice detectors could rival or surpass HgCdTe. That's the theory — but in practice, progress was limited by the challenge of growing high-quality superlattices. But now, with improved materials such as those being produced by MDL's new third-generation Veeco MBE system, this prediction is starting to become reality. Furthermore, as opposed to QWIPs, superlattice detectors exhibit strong absorption for normal-incidence radiation, simplifying detector design and enabling

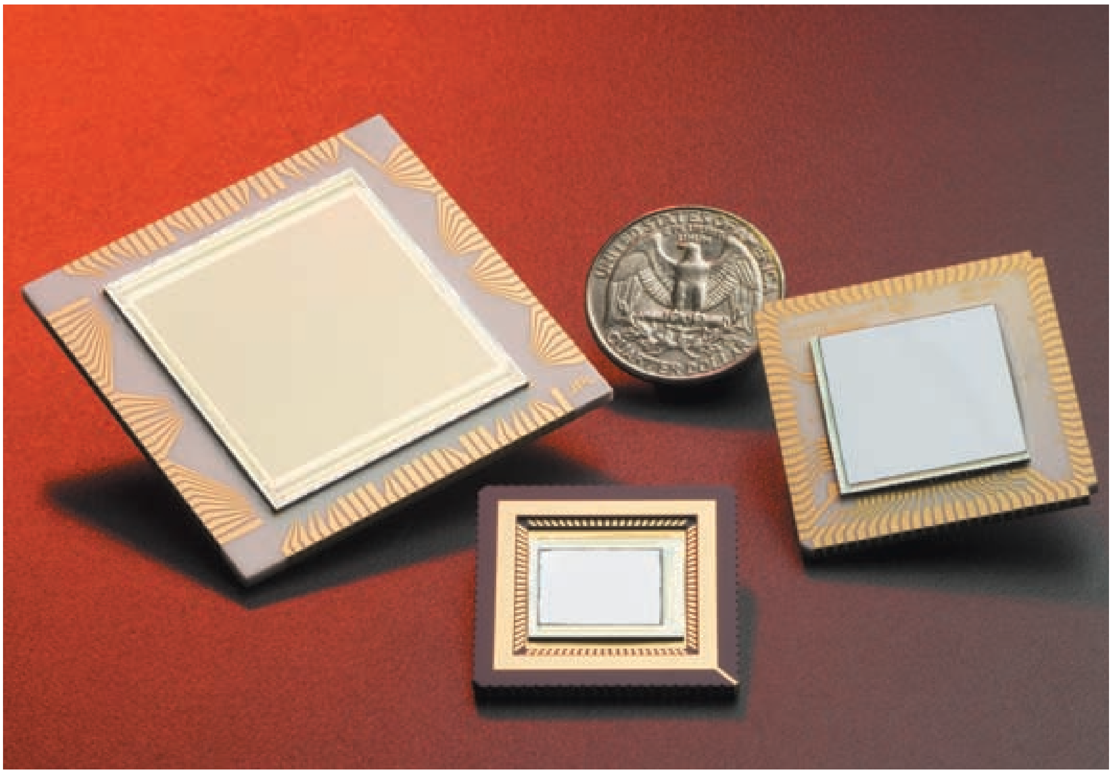
improvements in quantum efficiency. Furthermore, MDL's MBE system is capable of processing 100-mm wafers, allowing array formats up to 16 megapixels to be produced.

3. QUANTUM DOT INFRARED PHOTODETECTORS (QDIPS): One of the challenges for QWIP detectors is the fact that they do not absorb normal-incidence radiation, and therefore require a grating structure to scatter the photons sideways to achieve absorption. Another approach for improving the absorption efficiency is to break the in-plane translational symmetry of the quantum well that prevents normal-incidence absorption. This can be done by modifying the epitaxial growth to produce small separated nanoscale islands of material known as "quantum dots" instead of continuous crystalline layers, resulting in QDIPs instead of QWIPs. QDIPs thus share the fabrication advantages enjoyed by QWIPs but should offer better sensitivity.

4. QUANTUM-WELL INTERSUBBAND PHOTODETECTORS (QWISPS): This is an exciting new concept for far-infrared detectors (50–300 μm) using quantum wells. The structure is very similar to a QWIP, except that the quantum-well layers are grown with very high doping. While there are several other benefits resulting from the high doping, one effect is especially important: momentum scattering by the dopant impurities allows strong absorption of normal incidence radiation. Combined with the use of QWIP-like manufacturing techniques and multiplexed readouts, large arrays should be possible. This would be a tremendous advance compared to today's state of the art of labor-intensive, hand-crafted, highly mechanically stressed, individually assembled Ge:Ga detectors such as those now used in the MIPS instrument on JPL's infrared space observatory, the Spitzer Space Telescope. The next step is to turn theory into practice!



Schematic band diagram of a superlattice. This diagram shows the alternating layer structure of a superlattice in schematic fashion. The unusual relative alignment of the valence and conduction energy bands in InAs and Ga(In)Sb allows the formation of two "minibands" with a small energy separation — perfect for long-wavelength infrared detectors.



A selection of QWIP arrays, clockwise, starting at the lower left: 640 x 512 single band, 320 x 256 dual band, 1024 x 1024 single band, 1024 x 1024 dual band.

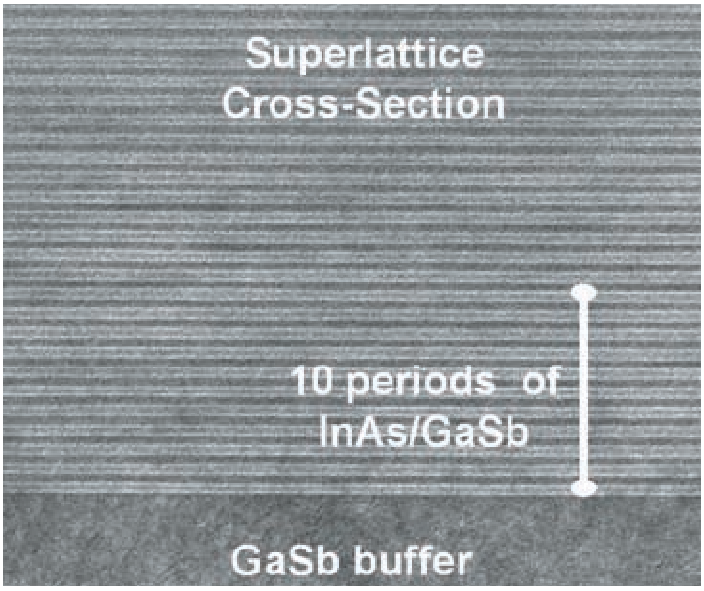
2007 Highlights

QWIPS: Techniques for fabricating larger QWIP arrays continue to be developed. These techniques, while demonstrated using QWIPs, are also applicable to other detector types — QDIPs, QWISPs, etc. For example, the fabrication of a 1K x 1K dual-band (4 and 9 µm) array required the development of a technique to combine multiple exposure fields of MDL's photolithographic stepper — a technique that opens the path to 2K x 2K and 4K x 4K arrays. Another new development is the demonstration of polarized QWIP pixels. These devices use a built-in 1D grating structure to scatter only one polarization of the incoming radiation sideways, while the other polarization remains at normal incidence and is not absorbed. The megapixel QWIP focal planes have shown 100% pixel operability and extremely high pixel-to-pixel uniformity (99.99%).

SUPERLATTICE DETECTORS AND ARRAYS: A major advancement was the demonstration of a 256 x 256 long-wavelength (11 µm) superlattice array. In addition, excellent results for individual superlattice detectors were published, showing a peak quantum efficiency of 30% and broad response in the 6–12 µm range, as well as a room-temperature quantum efficiency of over 60% in the 2–3 µm range. These results indicate that superlattice detectors offer the highest potential for uncooled planetary instruments operating in the mid-infrared (3–5 µm) wavelengths, and should also be a strong competitor for long-wavelength (14 µm) low-background applications.

QDIPS: JPL made the first demonstration of a large, long-wavelength QDIP array — a 640 x 512 array operating at 8 µm. These results were published along with measurements of individual detectors, which showed that the QDIP response to normal-incidence radiation is indeed much higher than for QWIPs. The quantum mechanics of radiation absorption in QDIPs was also analyzed theoretically in a separate paper. Future work will focus on improving the measured quantum efficiency (around 20%) by optimizing the growth of the QDIP layers.

QWISPS: A theoretical paper describing the QWISP concept and performance calculations was published in *Applied Physics Letters*. These results show that QWISPs could potentially be used out to very long wavelengths, 300 µm or beyond.



Above: An electron microscope image of the alternating layers in a superlattice. Below: An image from JPL's first 256 x 256 superlattice array.

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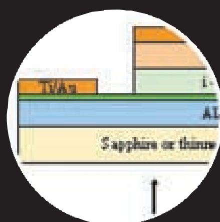
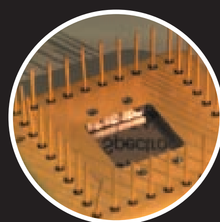
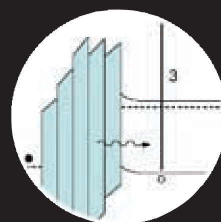
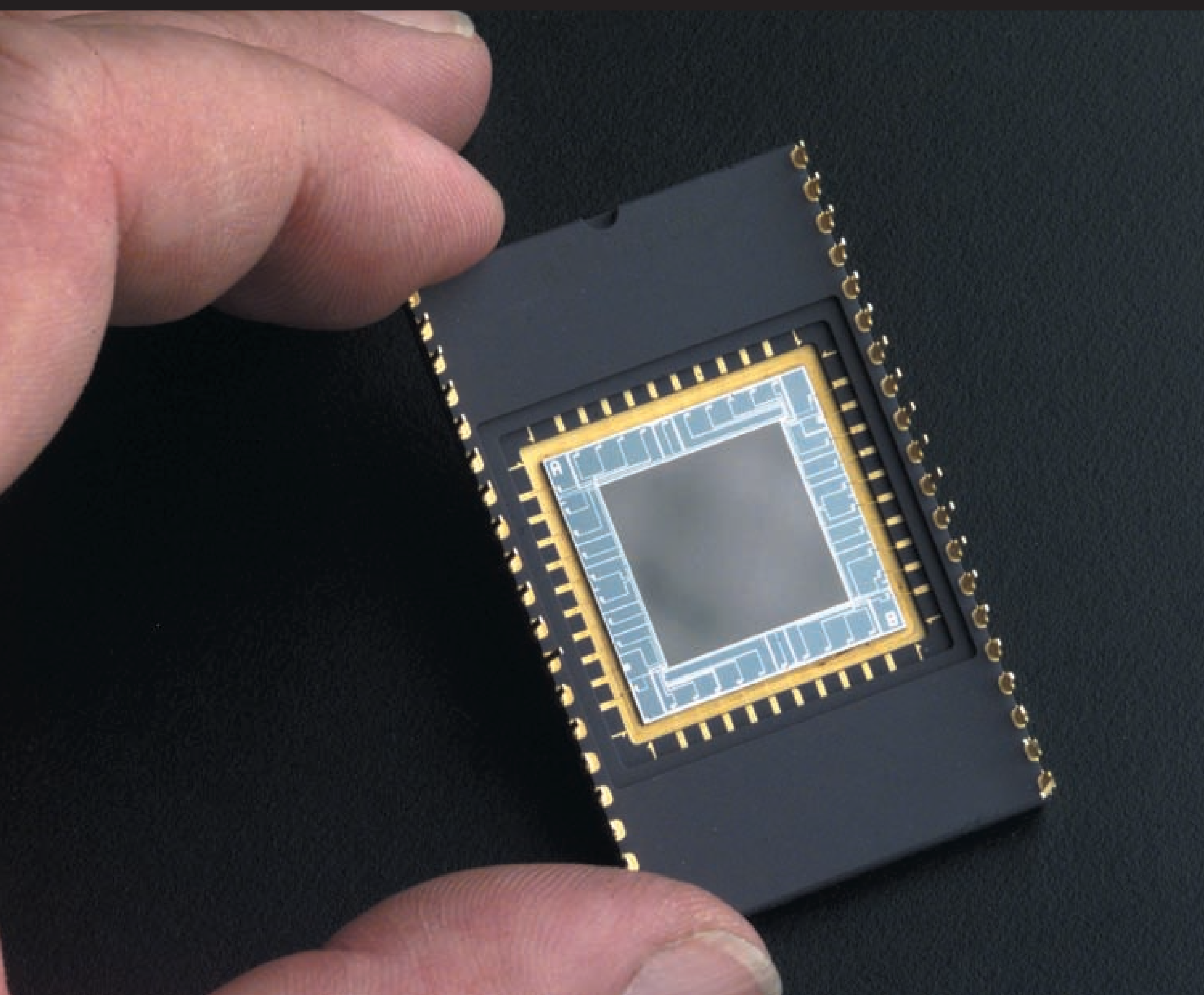
Advanced Ultraviolet, Visible, and Near-Infrared Imagers

High-performance imaging at ultraviolet (UV), visible, and near-infrared (IR) wavelengths is fundamental for space science. The applications span an enormous range, from measurements of the newly discovered but quite mysterious "dark energy" pervading the universe to studies of planetary atmospheres and even life detection. Silicon imaging devices dominate at visible wavelengths, and can be found in digital cameras, webcams, cell phone cameras, etc. Their development traces back to 1969 when the silicon charge-coupled device (CCD) was invented at Bell Laboratories. The CCD quickly caught NASA's interest since planning for a space telescope (to become the Hubble Space Telescope, or HST) was underway. JPL guided the development and refinement of CCD technology, resulting in JPL's Wide Field / Planetary Camera (WF/PC) for HST. Several MDL staff served on a JPL Tiger Team in the late 1980s to investigate a problem that had arisen with WF/PC's UV response. This led to a very clever solution proposed by Dr. Frank Grunthaner and later demonstrated by a JPL team including Drs. Paula Grunthaner and Michael Hoenk. This solution, known as "delta-doping," is unique to JPL and uses the molecular-beam epitaxy (MBE) atomic-layer growth technique (see the Infrared Detector section) to place a dense layer of charge just below the silicon surface. The UV photons are absorbed very near the surface, and the buried charge layer prevents the photo-produced charges from being trapped at the surface and thereby escaping collection and detection. Delta-doping also offers considerable performance benefits across the entire UV to near-IR spectrum. For example, delta-doped devices are exceptionally uniform and stable, and have extremely low dark currents.

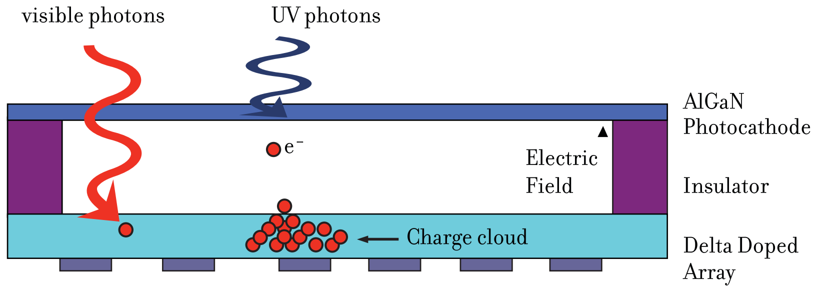
Building on the experience with delta-doping, similar epitaxial non-equilibrium techniques are now being applied to silicon, gallium nitride, and other material systems to alter the electronic band structure, interface structures, and to form quantum dots. In addition, wafer thinning and bonding techniques are used to create devices with unusual mechanical structures or properties. Examples include solar-blind UV imagers, devices with voltage-tunable wavelength response, flexible imagers for curved focal planes, and even silicon-compatible infrared detectors.

Current Projects

1. DELTA-DOPED IMAGERS have substantial performance advantages for astrophysics and cosmology, as demonstrated through our work with the Lawrence Berkeley National Laboratory's (LBNL) Supernova Acceleration Probe (SNAP) project. SNAP is a leading contender for the upcoming Department of Energy (DOE)/NASA Joint Dark Energy Mission. In addition to providing the exceptionally broad UV to near-IR spectral coverage needed for SNAP, the use of delta-doped CCDs also streamlines the fabrication process significantly — a key benefit for SNAP's gigapixel focal plane. Another mission opportunity is the ISTOS Small Explorer concept being proposed by Caltech and JPL to study the large-scale structure of the universe — the "cosmic web." Delta-doped CCDs with an integrated gain register that allows UV photon

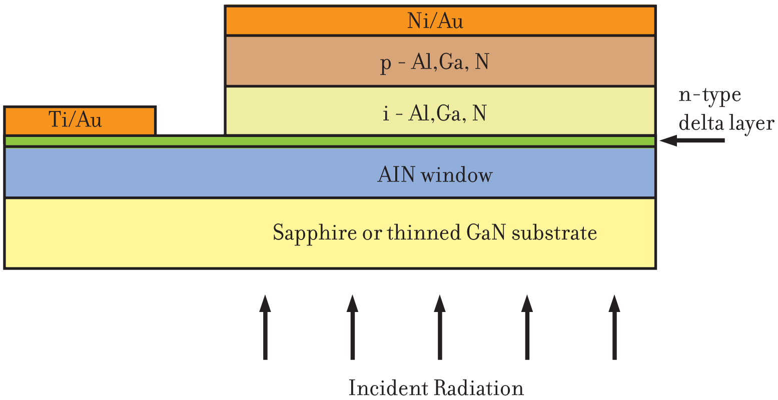
counting are currently baselined for ISTOS. Delta-doping is not restricted to CCDs — megapixel delta-doped back-illuminated CMOS arrays hybridized with a custom readout circuit have been demonstrated at MDL, and shown to have improved efficiency and enhanced spectral response.

2. GaN PHOTOCATHODES: Solar-blind UV imaging is often required, but this is difficult to accomplish with silicon devices. Cesiated photocathodes have been used but are unreliable and cannot be exposed to air. At MDL, robust GaN materials and MBE techniques are being applied to develop Cs-free solar-blind photocathodes.



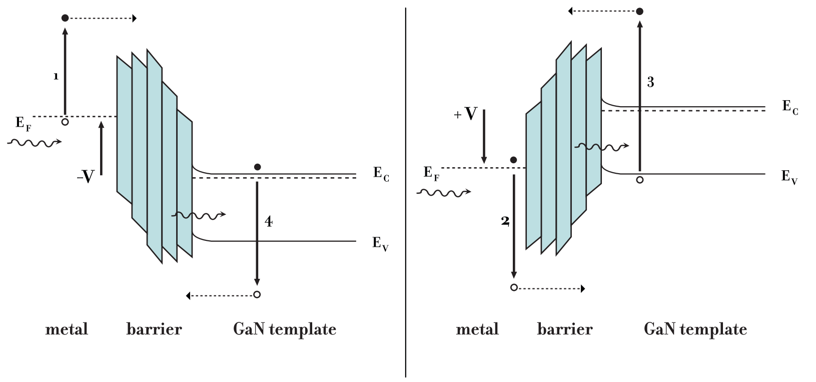
Schematic of a low-voltage electron bombarded array featuring a delta-doped array for low-energy electron detection, Cs-free photocathode, and novel low-noise operation for proximity focus configuration.

3. GaN ARRAYS: Another approach to solar-blind UV imaging is to fabricate detectors using large-bandgap semiconductors such as gallium nitride and its alloys. Our interface-engineered p-i-n GaN detector design achieves high quantum efficiency and low leakage, and the detector array can be hybridized with a commercially available CMOS readout to produce a complete large-format imager.



Schematic of an interface-engineered GaN pin detector structure featuring a thin AlN window grown directly on sapphire or GaN.

4. WAVELENGTH-TUNABLE DETECTORS enable the construction of spectrometers with substantially reduced weight, size, and complexity. A new type of detector is under development, based on electron barriers fabricated from layered dielectric materials. The voltage-tunable potential barrier provides energy selectivity for collection of photoelectrons, and therefore an adjustable wavelength response.



Biasing the layered barrier structure determines which photo-absorption processes are enhanced and which are suppressed.

5. NEAR-IR DETECTORS: Current low-bandgap (HgCdTe) infrared imagers must be mated to a separate silicon-based readout circuit, substantially increasing cost and complexity. However, low-bandgap SnGe thin films can now be grown on silicon substrates at the MDL using MBE techniques, opening new options for monolithic, low-cost, large-format silicon-based imagers for the 1–5 µm wavelength range.

2007 Highlights

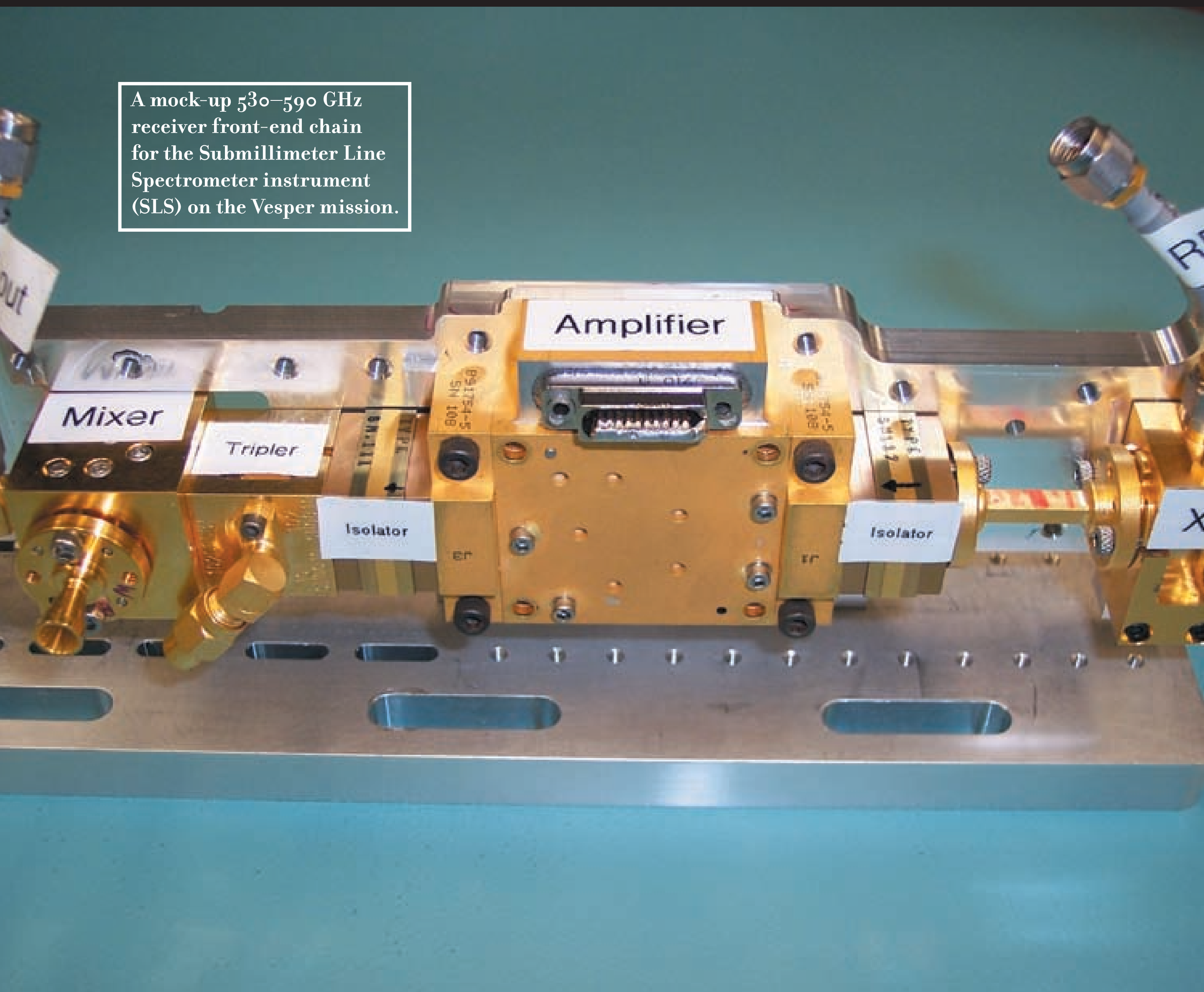
1. DELTA-DOPED CCDs: The first large-format, delta-doped CCD was demonstrated. This 8-megapixel, 2k x 4k device had excellent performance characteristics: high efficiency, excellent uniformity, high resolution, and low dark current. A collaboration with LBNL and Lick Observatory resulted in the first galaxy image obtained with this device.

2. CURVED FOCAL PLANE ARRAYS: The first images were obtained with our thinned variable curvature arrays.

3. WAVELENGTH TUNABLE DETECTORS: Control of barrier height and a tunable wavelength response were demonstrated using layered III-N heterostructure detectors. External quantum efficiencies of over 12% have been achieved, two orders of magnitude better than previous work. Sensitivity in both visible and UV bands has been achieved in a single device, and growth on silicon substrates has been demonstrated.

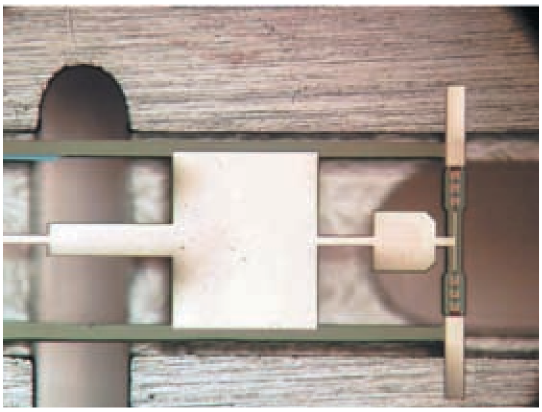
4. NEAR IR DETECTORS: Single-crystal SnGe films 200–300 nm thick containing up to 11% Sn have been grown by MBE on silicon wafers, as well as prototype Schottky detector structures.

Submillimeter Devices

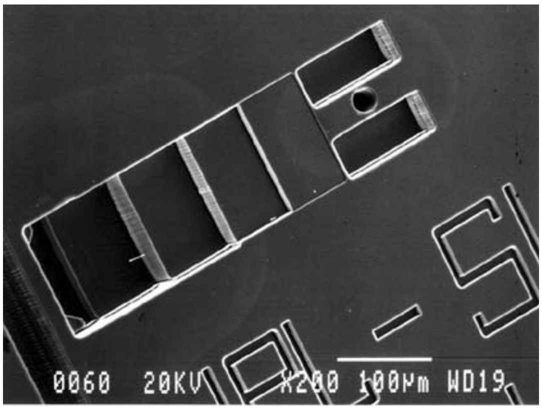


A mock-up 530–590 GHz receiver front-end chain for the Submillimeter Line Spectrometer instrument (SLS) on the Vesper mission.

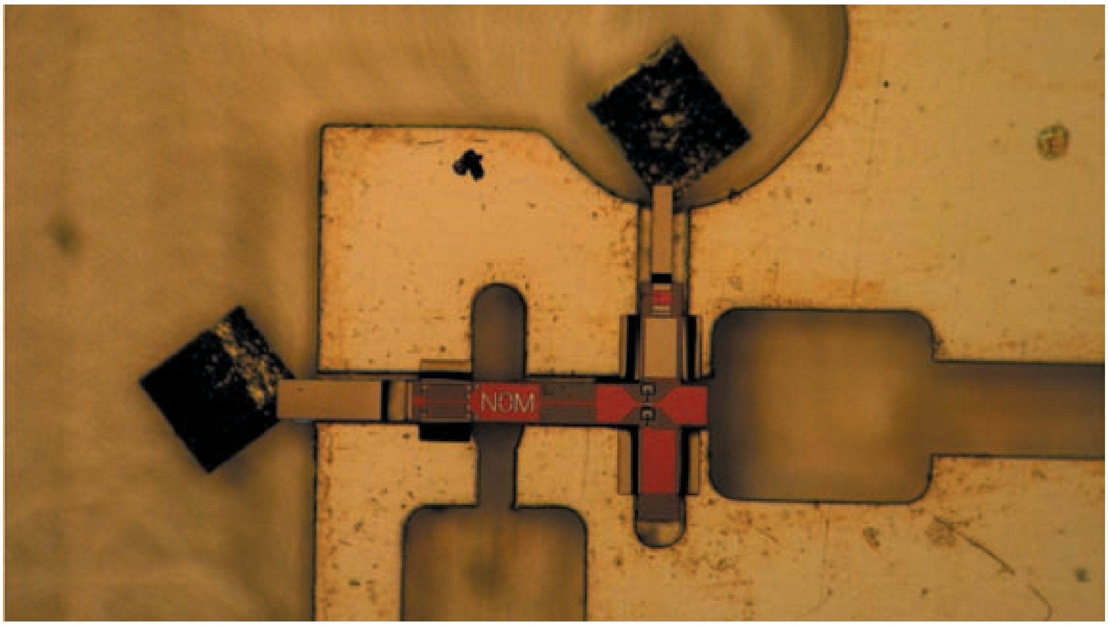
The Submillimeter-Wave Advanced Technology (SWAT) group develops technologies and instruments for remote sensing in the submillimeter wavelength band. There are numerous opportunities for submillimeter space instrumentation in Earth science, planetary exploration, and astrophysics. In fact, the SWAT group has already contributed mission-enabling flight hardware for several major projects, including the Earth Observing System (EOS) Microwave Limb Sounder (MLS) for studying the chemistry of Earth's atmosphere; the Microwave Instrument for the Rosetta Orbiter (MIRO), for examining the molecular species in the gaseous coma of comet Wirtanen; and the "HIFI" heterodyne instrument for the Herschel Space Observatory, a submillimeter astrophysics mission. In addition, there are ground-based spin-off applications. The submillimeter band is quite difficult from a technology standpoint since the frequencies are generally too high for semiconductor electronic devices, while the wavelengths are too long for semiconductor photonic devices. This is the so-called "terahertz gap." The MDL therefore plays an especially critical role, providing a facility for fabricating devices that are specifically designed and optimized for submillimeter operation. For example, JPL has pioneered submillimeter solid-state frequency sources and radio receivers, and now holds world records for power produced, efficiency, bandwidth, and frequency. The secret? Highly optimized GaAs Schottky diodes on very thin silicon nitride membranes using submicron anodes defined by electron-beam lithography.



200-GHz high-power multiplier chip (JPL).



1200-GHz MEMS nanoklystron cavity (JPL).



600-GHz balanced waveguide mixer.

Current Projects

1. VESPER is a Discovery-class mission with the goal of studying the atmosphere of Venus in detail. One of VESPER's key instruments is the Submillimeter Line Spectrometer (SLS), an instrument tunable over the 440–500 and 530–590 GHz bands.

2. A GLOBAL ATMOSPHERIC CHEMISTRY MISSION (GACM) was endorsed in the NRC decadal survey and could include a submillimeter instrument, the Scanning Microwave Limb Sounder (SMLS). Very sensitive superconducting (SIS) mixers for the 180–280 GHz and 560–680 GHz bands are being developed for SMLS.

3. SCHOTTKY DIODE balanced fundamental mixers for the 500–600 GHz range are under development for a future Mars atmospheric sounder.

4. BUILDING ON PIONEERING WORK FOR HERSCHEL/HIFI, a small explorer (SMEX) astrophysics mission is proposed to study the bright galactic emission lines of ionized nitrogen at 1.46 THz and ionized carbon at 1.9 THz.

5. HOT-ELECTRON BOLOMETER (HEB) RECEIVERS: A small effort is devoted to developing waveguide-based superconducting hot-electron bolometer (HEB) receivers, also for the SMEX project.

6. TERAHERTZ IMAGING: This is a Navy-funded effort to develop the technology for detecting concealed weapons or contraband from standoff distances exceeding 20 meters. Active imaging (radar, in other words) at terahertz frequencies is attractive because the corresponding submillimeter wavelengths are short enough to provide high resolution with modest-sized antennas, yet long enough to penetrate materials such as cloth or cardboard.

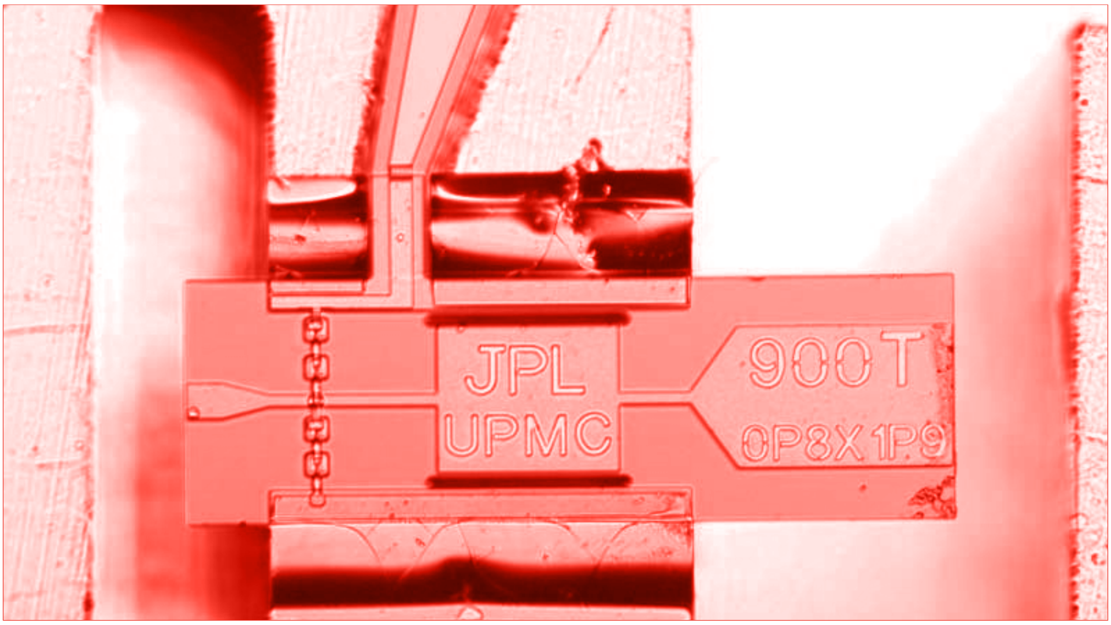
2007 Highlights

SCHOTTKY DIODE MIXERS: The JPL-developed Monolithic Membrane Device (MoMeD) process for GaAs Schottky diodes allows chip-level integration of various features for increased functionality without sacrificing performance. Subharmonic mixers covering the 530–590 GHz range were demonstrated with sensitivities better than 5000 K. Novel balanced fundamental mixers have also been demonstrated, with sensitivities below 4000 K in the 530–590 GHz range and with less than 2 mW of required local oscillator power. These mixers are baselined for missions to Venus and Mars.

ACTIVE SUBMILLIMETER-WAVE IMAGING: A complete 600-GHz active imaging radar system was developed and demonstrated with 3D resolution better than 1 cm from a distance of 4 meters. The key components are MoMeD-based solid-state frequency sources with high transmit power, and low-noise mixers for sensitive detection. Proposals are now being developed for applications in planetary exploration, as a radar/spectrometer for trace-gas detection *in situ* on Mars or remotely on thin-atmosphere moons such as Europa.

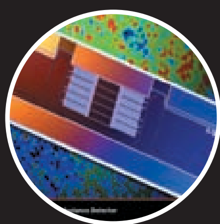
COMPACT SUBMILLIMETER-WAVE SOURCES: New performance records for solid-state frequency sources continue to be set. In 2007, a 200–270 GHz frequency tripler with 13 mW output power was demonstrated. Also, in a collaboration with the Université Pierre et Marie Curie in Paris, broadband sources at 300 GHz and 900 GHz were demonstrated with output powers of 22 mW and 600 µW, respectively.

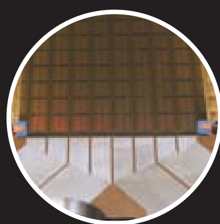
SIS RECEIVERS FOR STUDYING GLOBAL ATMOSPHERIC CHEMISTRY: A 180–280 GHz SIS receiver is under development for GACM/SMLS using SIS devices fabricated at the MDL according to a design developed at Caltech. These devices have world-class sensitivity and a very broad (>18 GHz) instantaneous bandwidth.

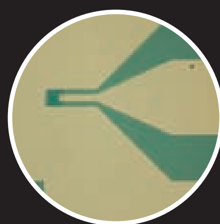


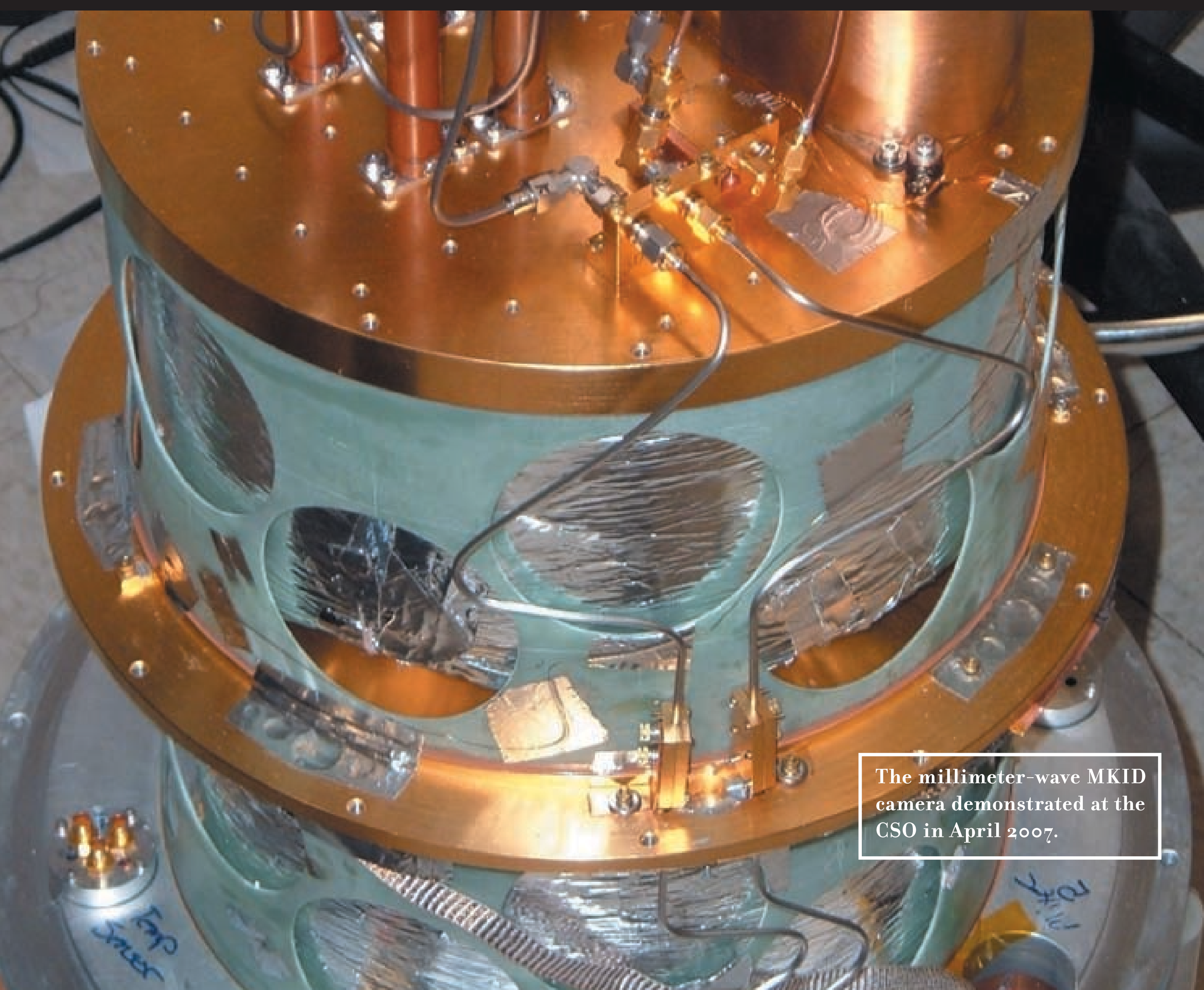
A 800–950 GHz frequency source, using an MDL-produced MoMeD.

{Superconducting Devices}



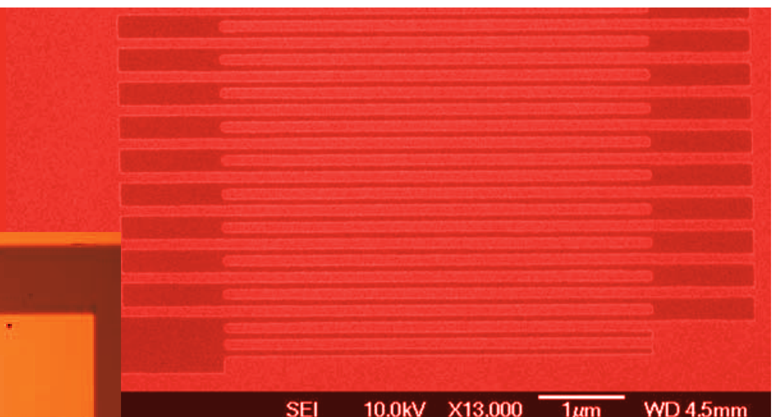


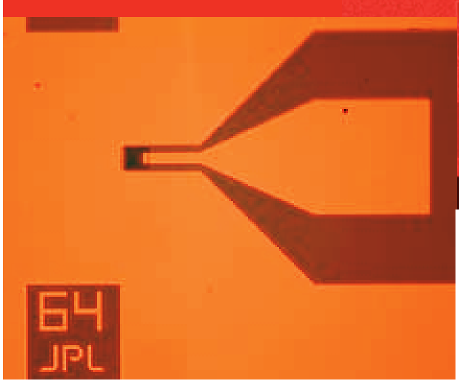




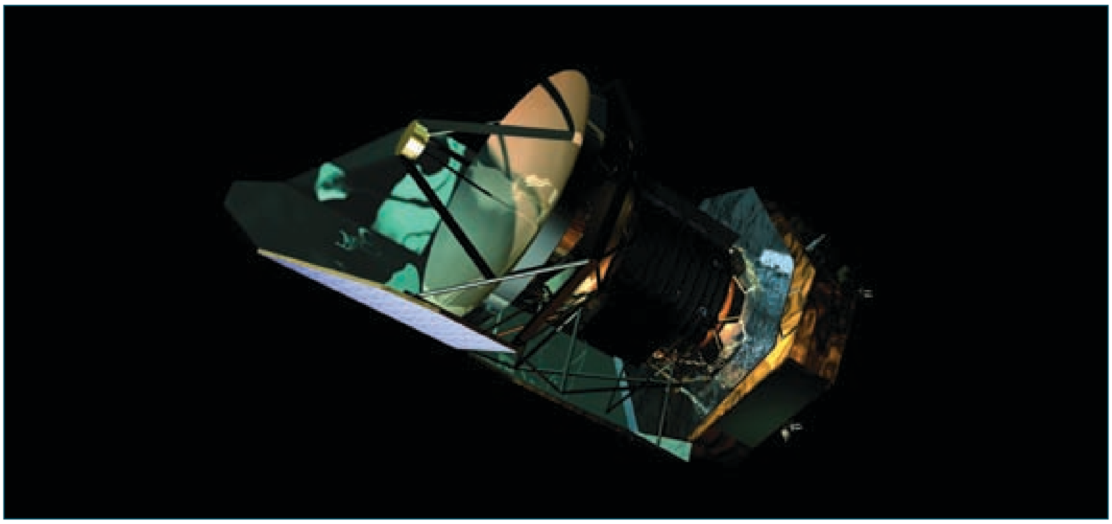
The millimeter-wave MKID camera demonstrated at the CSO in April 2007.

For applications that demand extreme sensitivity, such as space astrophysics, it is often necessary to cool detectors to very low temperatures in order to reduce noise. At these low temperatures, superconducting devices offer unique capabilities and performance advantages. The Superconducting Materials and Devices group at JPL has a 23-year history of developing superconducting devices for space applications. Initially the group focused on developing tunnel junction (SIS) mixers for high-resolution sub-millimeter spectroscopy, which involved a close collaboration with Caltech and culminated in the delivery of 1.2-THz SIS mixers for the HIFI instrument on board the Herschel Space Observatory (a European Space Agency mission, 2008 launch). These are the highest frequency SIS mixers ever produced, worldwide. The group has now broadened its scope and is developing sensors for a broad range of applications, including photon detection from millimeter to x-ray wavelengths. For example, there is a substantial effort to develop large-format polarimetric millimeter-wave detector arrays for measuring the polarization of the cosmic microwave background (CMB). The ultimate goal is the "CMB-pol" space mission, which will study the mysterious "inflation" that occurred in the very early universe. Other interesting non-sensor applications of superconducting devices are also emerging, such as quantum computing.





Left: An optical photograph of a superconducting nanowire single photon detector (SNSPD). Above: A scanning electron micrograph of the active area. This detector is 5 by 5 microns square with 0.10 micron wide wires on 0.2 micron spacing. The yellow material is a gold coplanar waveguide that carries the bias current and output signal.



The Herschel Space Observatory.

Current Projects

1. SIS MIXERS: see the Submillimeter-Wave Devices section.

2. TES BOLOMETERS: Transition-Edge Sensors (TESs) use superconductors to sense the very small temperature changes that occur in bolometric detectors when incoming radiation is converted to heat. TES bolometers are monolithically integrated with filters and antennas to produce millimeter-wave polarimetric focal plane arrays for cosmology experiments such as the Caltech/JPL SPIDER balloon project. TES arrays are also being developed for future far-infrared astrophysics missions such as SAFIR (Single Aperture Far-Infrared observatory), JPL's CALISTO concept, or the BLISS instrument proposed by JPL for the Japanese mission SPICA. The TES bolometers are replacing MDL/JPL's hugely successful "spider-web" semiconductor bolometer technology. The spider-web bolometers have had a huge impact on cosmology. For example, the Boomerang balloon experiment showed that the geometry of the universe is flat — a historical milestone in cosmology. The spider-web bolometers will be flying on ESA's Planck and Herschel missions.

3. MKIDS: the Microwave Kinetic Inductance Detector (MKID is a device invented at JPL and Caltech, and is being developed for photon detection from millimeter to X-ray wavelengths. Compared to other superconducting detectors, MKIDs are much simpler to fabricate and to assemble into a system, potentially allowing very large arrays to be developed for a broad spectrum of future astrophysics missions.

4. SNSPD: Superconducting Nanowire Single Photon Detectors (SNSPDs) are high-speed, high-efficiency single-photon detectors operating in the near-infrared that are needed for future space-to-ground optical communication links.

5. QUANTUM COMPUTATION: While extremely challenging technologically, quantum computation offers exponential speed-up for certain tasks, such as the many combinatorial optimization problems that pervade JPL's efforts

in mission planning and engineering design. Quantum computation may be possible using superconducting circuits, and some experiments in this area are in progress at MDL. In addition, since May 2005, JPL/MDL has collaborated with a small company, D-Wave Systems Inc., that hopes to commercialize quantum computing using a unique "adiabatic" approach.

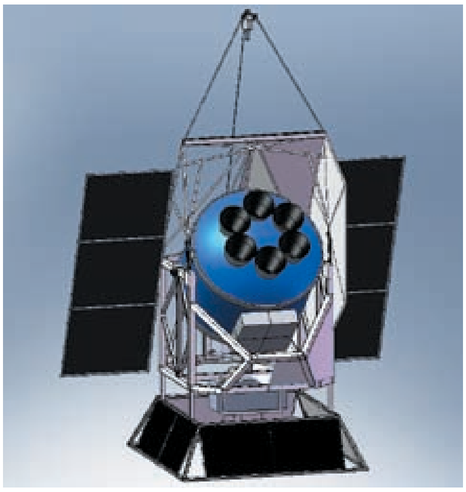
2007 Highlights

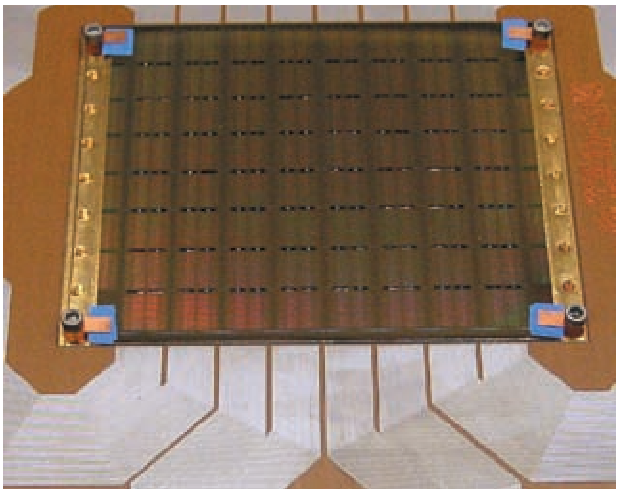
TES: Prototype polarimeter arrays have been designed, fabricated, and tested that now meet the requirements for the Caltech/JPL SPIDER balloon project. These arrays include a new on-chip antenna design with a 13-degree beam width and less than 3% cross-polarization. Results obtained this year also show that far-infrared TES bolometers could approach background-limited sensitivity for imaging and spectroscopy in space, and prototype 32 x 64 far-infrared TES imaging arrays were fabricated.

MKID: A prototype 4 x 4 pixel, two-color millimeter-wave MKID camera was designed, constructed, tested, and successfully demonstrated at the Caltech Submillimeter Observatory (CSO) in April 2007. In a Caltech/Colorado/JPL collaboration, NSF funding for a 24 x 24, four-color CSO camera was obtained. This is also a prototype instrument for the proposed 25-m CCAT telescope. An MKID-based optical imager with energy resolved photon counting is also being prepared for the 5-m Palomar telescope. The detector design was described in a 2007 paper in *Applied Physics Letters* and has significant potential for future planet finding (TPF-C) and UV/X-ray astrophysics missions. New funding for this work was recently awarded by the NASA/APRA program.

SNSPD: In 2007, SNSPD devices fabricated at MDL demonstrated world-record performance, with a 90% quantum efficiency for 1064-nm radiation, 25-ps, single-photon timing jitter and a dark count rate below 1 kHz, making them ideal for high-data-rate communication.

QUANTUM COMPUTATION: In February 2007, D-Wave announced its "Orion" processor, a 4 x 4 qubit array fabricated at JPL/MDL, and demonstrated its application to three problems.





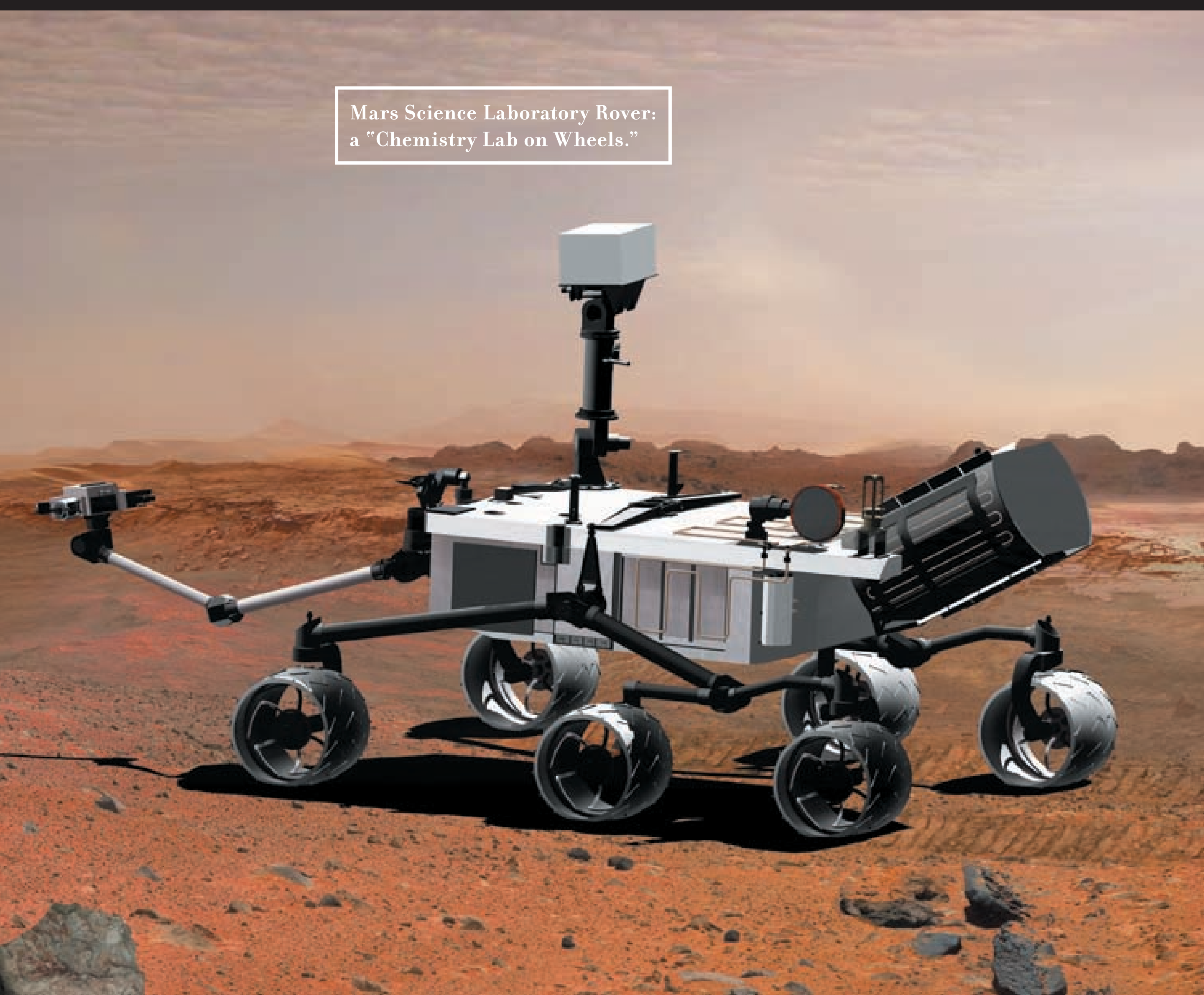
Left: A conceptual picture of the instrument package for the SPIDER balloon-borne CMB polarimetry mission. Each of the six telescopes looks at a different wavelength band. Right: A polarimeter "tile" with 64 pixels and 128 TES bolometers fabricated in MDL. Multiple tiles are required to fill the focal planes.

M D L 07 ANNUAL REPORT

Microdevices Laboratory

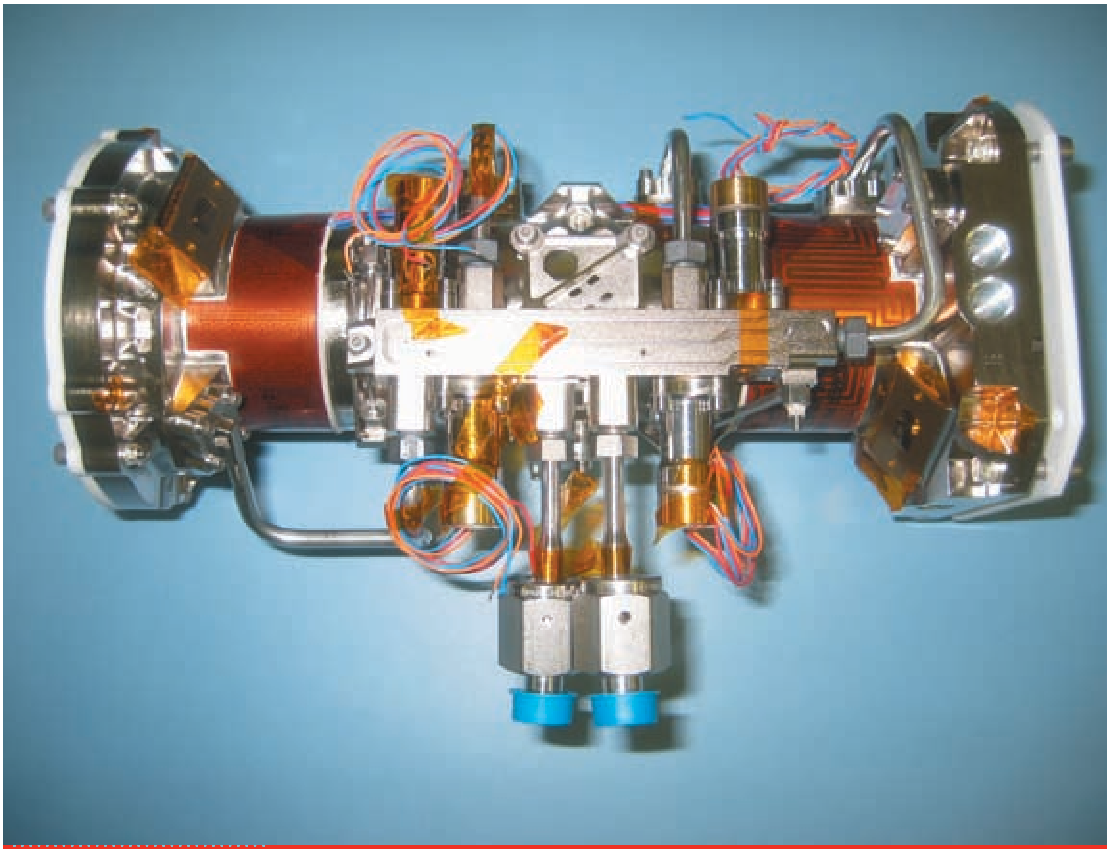
Semiconductor Lasers



Mars Science Laboratory Rover: a "Chemistry Lab on Wheels."

Semiconductor lasers were first demonstrated in the early 1960s and now have very widespread applications in commerce and science. NASA has a particular need for tunable infrared lasers, which are used for *in situ* high-resolution spectroscopy. In this technique, trace molecules in Earth's atmosphere or the atmosphere of another planet may be precisely identified and studied by measuring their infrared absorption spectrum. Such measurements can reveal a wealth of information about the atmosphere: its composition, chemistry, evolution, and winds. However, tunable infrared lasers with the characteristics needed for a particular measurement or mission are often not available commercially, and so a development activity was formed at MDL in the early 1990s. Early accomplishments included the development of the first semiconductor laser in the 1.8–2.1 µm range, which was delivered (Mars '98 mission) for the Mars Volatiles and Climate Surveyor (MVCS) payload to the Mars Polar Lander project. Spectroscopy in the mid-infrared (3–10 µm) is particularly powerful since the fundamental vibrational transitions of many molecules fall in this range. However, as is the case for infrared detectors, making a semiconductor laser that operates efficiently at these long-infrared wavelengths can be challenging. The earliest devices (mid-1960s) used exotic low-bandgap lead-salt semiconductors and required low cryogenic temperatures to operate — a severe limitation for a space project. While the lead-salt devices were used by JPL in atmospheric balloon-borne instruments, a much better solution appeared in 1994, when a new laser operating at higher temperatures was demonstrated by a group at Bell Laboratories — the quantum cascade laser (QCL). A QCL relies on the same epitaxial growth techniques that are used for infrared (QWIP) detectors. An even better solution was proposed in 1995, the interband cascade laser (ICL), but, like the superlattice infrared detectors, this device requires use of trickier materials (AlSb, GaSb, InAs) instead of the standard AlGaAs/GaAs, so the initial progress was slower. However, since 2002 a strong effort was made at MDL that led to the successful development of mid-infrared ICL devices. MDL's IC lasers have now been integrated into laser spectrometers and used in JPL aircraft and balloon experiments for measuring atmospheric HCl and CH_4 profiles. In addition, the development of 3.27-µm IC lasers for detection of the isotopes of methane proved to be an important factor for the selection of a JPL instrument, the Tunable Laser Spectrometer (TLS), on the Mars Science Laboratory (MSL). MSL is a Mars rover mission scheduled to launch in the fall of 2009 that will assess whether Mars ever was, or is still today, an environment able to support microbial life. The methane and carbon dioxide measurements provided by the TLS instrument will add unique and essential information needed to answer this fundamental question.



The optics assembly for the Tunable Laser Spectrometer instrument for the Mars Science Laboratory mission.

Current Projects

With the delivery of the space-qualified 3.27-µm lasers for TLS, JPL is currently the world leader in 3–5 µm tunable semiconductor lasers. The TLS IC lasers are single mode with output powers of 1–2 mW. Our current emphasis is to increase the output power by an order of magnitude to enable Quartz Enhanced Photo-Acoustic (QEPA) spectroscopy. A second thrust is to extend the wavelength coverage of IC lasers to 3.53 µm for the detection of H_2CO (formaldehyde), HCl, and HCN as combustion products.

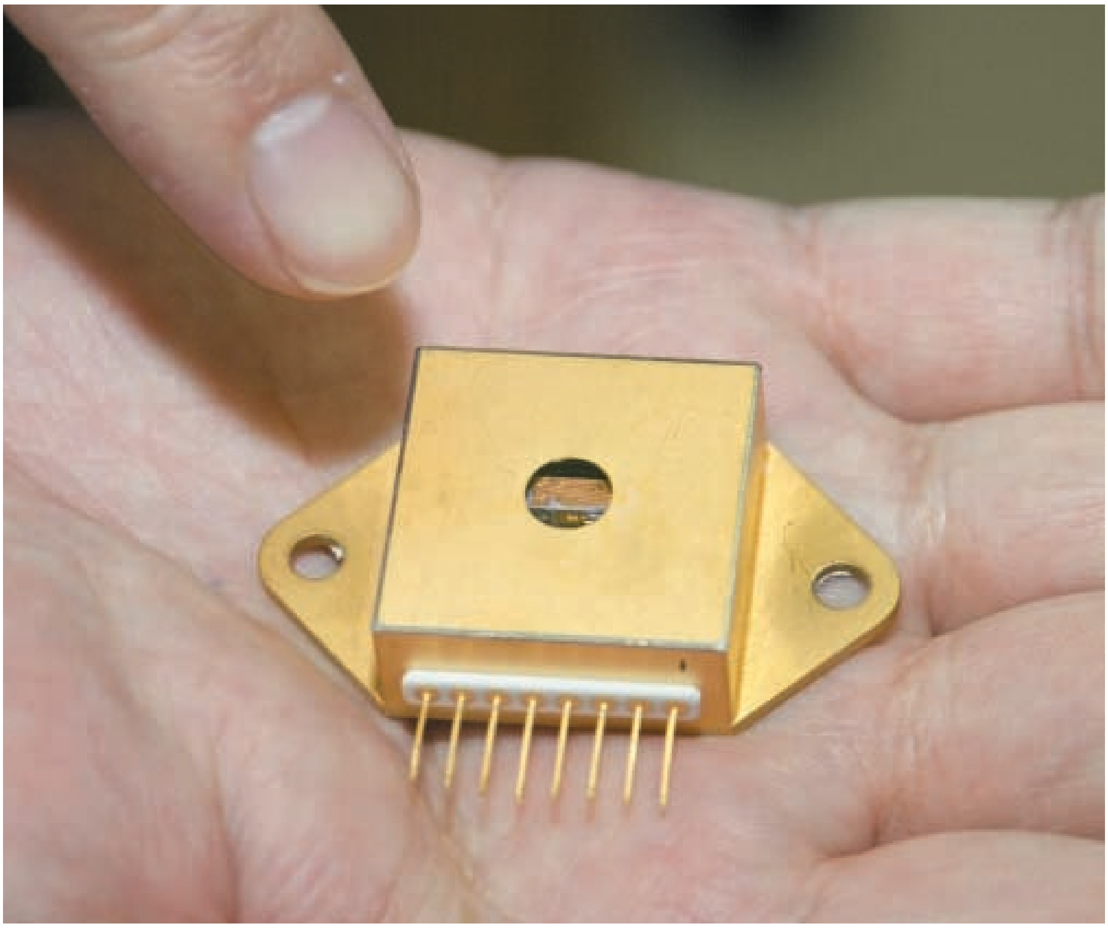
2007 Highlights

IC LASER MODULES were successfully delivered for integration into the TLS/MSL instrument. These distributed-feedback, single-mode ICLs were hermetically sealed and thermoelectrically cooled.

PROGRESS ON THE TLS INSTRUMENT is illustrated by a quotation from Chris Webster, the Principal Investigator for TLS: "…the awesome accomplishment of actually having a JPL/MDL flight IC laser installed in TLS producing great output power after the cell, aligned to the right number of passes, scanning exactly over the methane target region of CH_4 and $^{13}CH_4$ lines, and showing the expected line absorption levels. Wow." (July 27, 2007)

ED STONE AWARD RECIPIENT: Rui Yang, who originally proposed the ICL concept in 1995, was a recipient of the 2006 Ed Stone Award for Outstanding Research Publication, for an *Applied Physics Letters* paper describing his MDL team's development of ICL technology for MSL/TLS.

A hermetically sealed, space-qualified, 3.27-micron IC laser for MSL/TLS.



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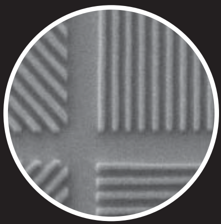
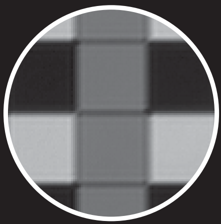
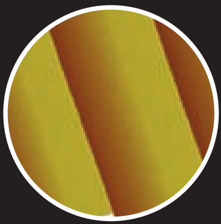
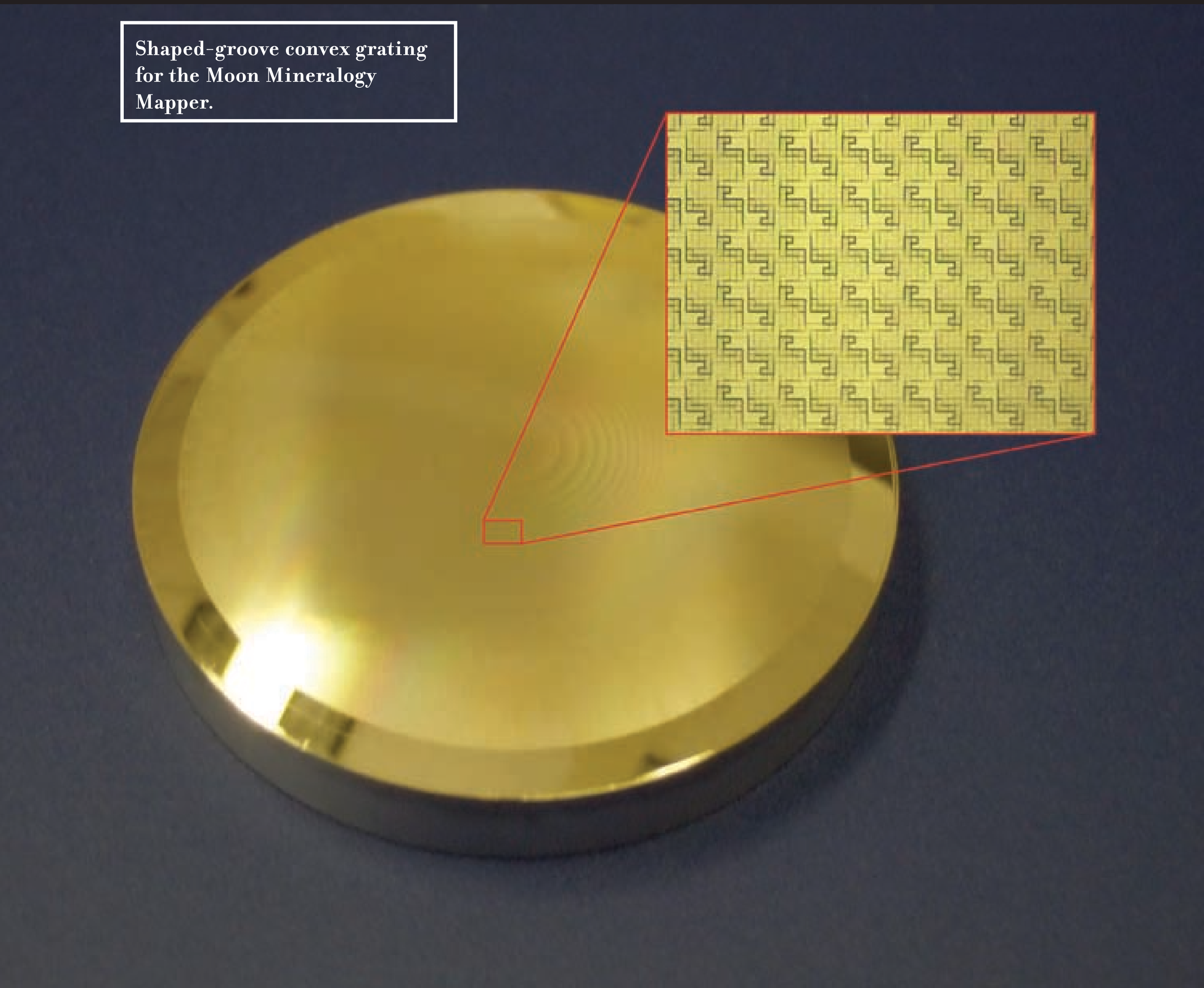
Microdevices Laboratory

Optical Components



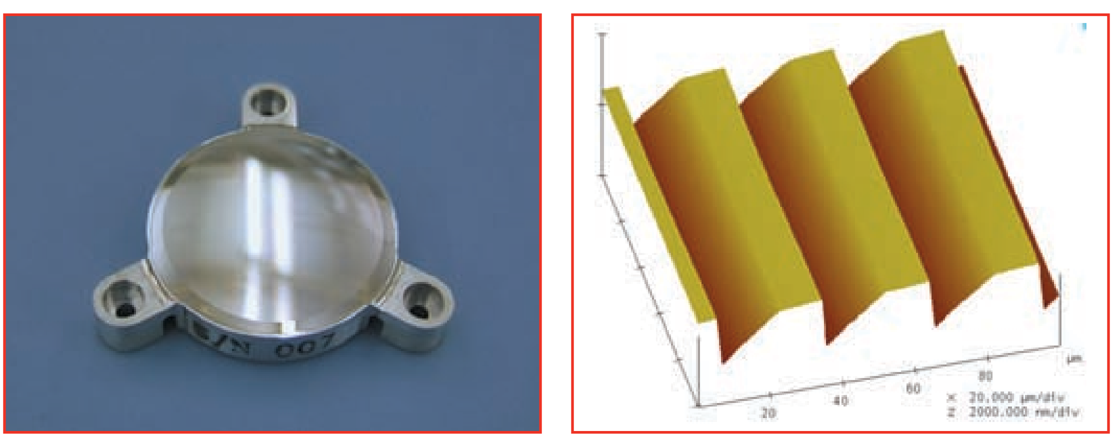


Shaped-groove convex grating for the Moon Mineralogy Mapper.

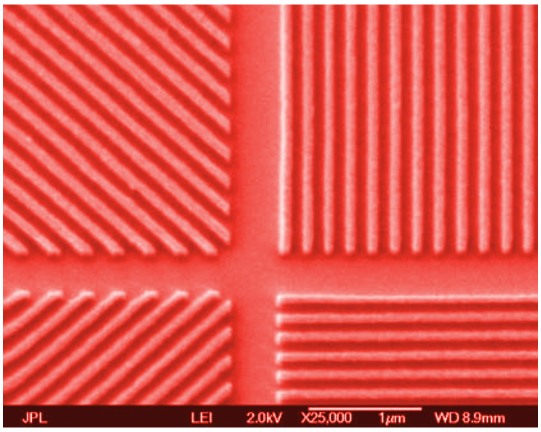
Using MDL's primary and very flexible tool for nanoscale patterning, the electron-beam lithography system, unique diffractive optical elements have been developed that enable a variety of instruments, including a number of airborne and spaceborne imaging spectrometers. Fabrication of diffraction gratings dates back to the 19th century, but the field of lithographically fabricated diffractive optics began in the 1960s with Lohmann and Brown at IBM, who used computer plotters and photo reduction. As lithography technology advanced, it became possible to fabricate diffractive optics by etching binary-level surface relief profiles that allowed tailoring of the phase of the optical waterfront. When this was combined with computer-generated hologram (CGH) design algorithms, sophisticated wavefront engineering became possible.

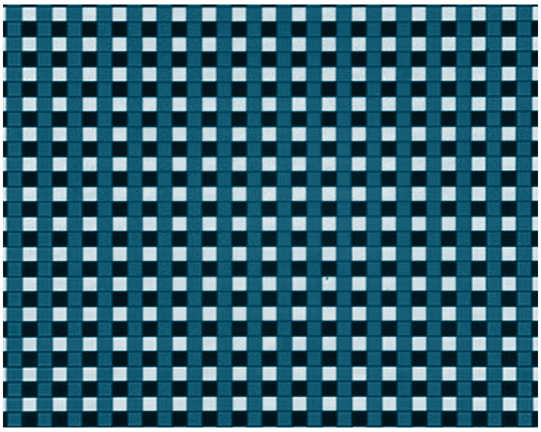
The MDL entered this field in the early 1990s when electron-beam techniques were developed for fabricating analog (rather than binary) surface-relief diffractive optics. These precise analog surfaces exhibit very high wavefront accuracy and efficiency. This technique has been used to produce microlenses for focal-plane arrays, gratings, and computer-generated holograms for optical interconnects and computed-tomography imaging spectrometers. During the late 1990s, JPL's spectrometer designers needed blazed gratings on convex spherical substrates for compact imaging spectrometers. Taking advantage of the electron-beam's significant depth-of-focus and precise calibration facilities, we developed schemes for fabricating analog surface profiles on substrates having several millimeters of center-to-edge height variation. This ability allowed the fabrication of high-efficiency (>90%) convex gratings for so-called "Offner" imaging spectrometers that are compact and can be designed to exhibit near-perfect spectral imaging.

The recent advent of extremely broadband focal-plane arrays (responding to wavebands as wide as 0.4 to 3.0 µm) stimulated the development of gratings that had usable efficiency over multiple octaves. One solution is the dual-blaze grating, composed of areas that are blazed for different wavelengths. This approach was used to fabricate gratings for the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) that is flying aboard Mars Reconnaissance Orbiter. In an effort to improve on the multiblaze scheme, shaped-groove gratings (SGGs) were developed, in which the groove is computer optimized to achieve a desired efficiency vs. wavelength response. This is very useful to the spectrometer designer since it allows equalizing the overall signal-to-noise level of the instrument across the band, taking into account both the source spectrum and the detector responsivity.



Photograph and surface profile of the shaped-groove convex grating for the Moon Mineralogy Mapper.





Left: Scanning electron microscope image of pixelized-wire grid polarizers. Right: Transmission image of polarizer array illuminated with polarized light.

Current Projects

1. CONVEX AND CONCAVE GRATINGS: Higher performance convex and concave diffraction gratings continue to be developed. The emphasis is on minimizing polarization sensitivity and scatter without sacrificing spectral efficiency. We are also fabricating concave gratings for extremely compact "Dyson" spectrometers.

2. CORONAGRAPH OCCULTING MASKS AND SHAPED PUPILS: Gray-scale occulting masks and complex-shaped open pupils are required for Terrestrial Planet Finder (TPF) coronagraphs to perform very high contrast (~10^{-10}) imaging for detecting Earth-like planets orbiting nearby stars. Precise gray-scale functions are fabricated in high-energy beam sensitive (HEBS) glass by E-beam lithography, and shaped-pupils in silicon by deep reactive-ion etching.

3. PATTERNED WIRE-GRID POLARIZERS: Polarization imaging provides information about the shape and roughness of features in a scene, and hence can be used to identify objects or to separate human-made objects from naturally occurring features. We are fabricating pixelized wire-grid polarizer arrays and integrating them with visible focal plane arrays.

4. COMPUTED-TOMOGRAPHY IMAGING SPECTROMETERS (CTISs): The CTIS enables snapshot imaging spectrometry of transient phenomena. We are currently designing and fabricating Offner-form reflective CTIS systems that utilize convex 2D computer generated hologram gratings and novel InGaAs near-IR and mid-IR QWIP focal plane arrays.

5. FLUID FLOW SENSOR OPTICS: In collaboration with Measurement Science Enterprise, we are designing and fabricating diffractive optical elements (DOEs) that enable non-invasive fluid flow sensors. The DOEs produce high-intensity light patterns in the fluid and particles in the flow scatter the light, allowing determination of fluid velocity and shear stress.

2007 Highlights

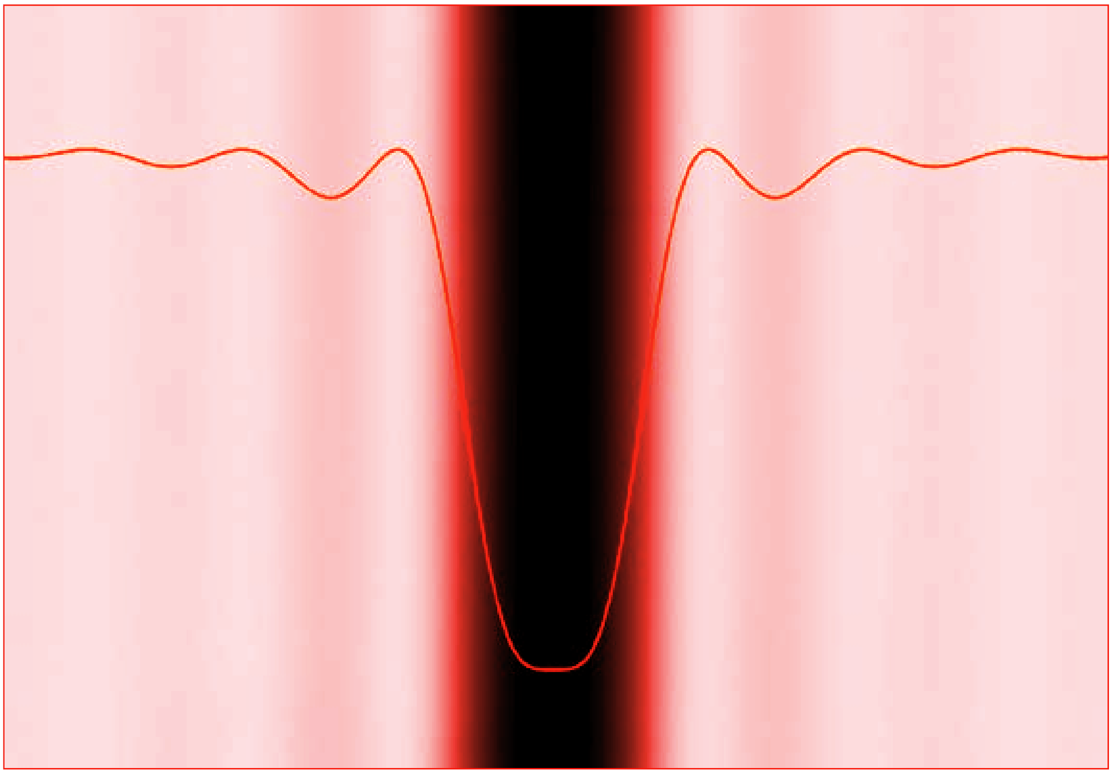
CONVEX AND CONCAVE GRATINGS: We utilized our shaped-groove grating technique to deliver broadband convex gratings for two space flight projects: (1) We designed and fabricated tri-linear groove gratings that produced tailored efficiency from 0.43 to 3.0 µm for the Moon Mineralogy Mapper spectrometer that will launch on India's Chandrayaan-1 in 2008; (2) We designed and fabricated bi-linear groove gratings for ARTEMIS (Advanced Responsive Tactically Effective Military Imaging Spectrometer) developed by Raytheon in collaboration with JPL. ARTEMIS will fly on the U.S. Department of Defense Tactical Satellite 3 (TacSat3).

CORONAGRAPH OCCULTING MASKS AND SHAPED PUPILS: Gray-scale HEBS masks and shaped pupils were fabricated that allowed JPL's high-contrast imaging testbed (HCIT) to achieve world-record imaging contrast ($<3\times10^{-9}$ over 10% spectral bandwidth).

PATTERNED WIRE-GRID POLARIZER ARRAYS: An array of pixelized wire-grid polarizers was fabricated and bonded onto a CMOS focal plane array. The polarization sensitive FPA was integrated into a camera and used to demonstrate visible-band polarization contrast imaging; self-aligned bi-layer pixelized polarizers were fabricated that exhibit contrast >500:1.

COMPUTED-TOMOGRAPHY IMAGING SPECTROMETERS: In collaboration with USC Doheny Eye Institute, we successfully demonstrated *in vivo* spectral imaging of the retina and showed that oxygen saturation maps could be obtained.

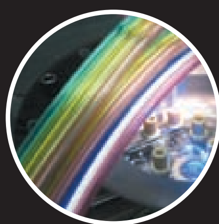
Transmission image of gray-scale occulting mask for TPF coronagraph, showing desired function.

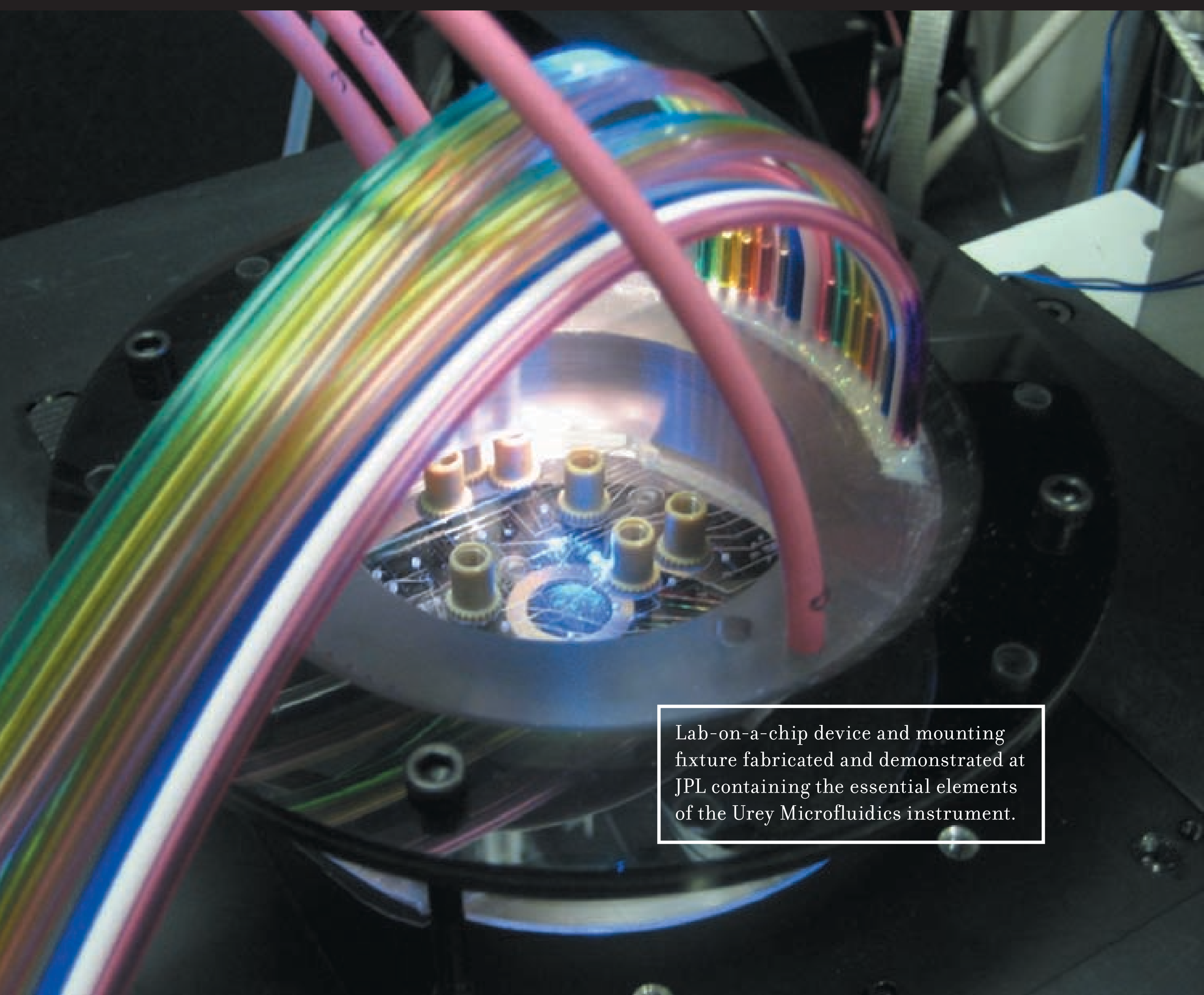


MDL 07 ANNUAL REPORT

Microdevices Laboratory

{Urey: Life-Detection Suite of Instruments}





Lab-on-a-chip device and mounting fixture fabricated and demonstrated at JPL containing the essential elements of the Urey Microfluidics instrument.

Surely one of the most marvelous feats of the 20th century would be firm proof that life exists on another planet. All the projected space flights and the high costs of such development would be fully justified if they were able to establish the existence of life on either Mars or Venus.

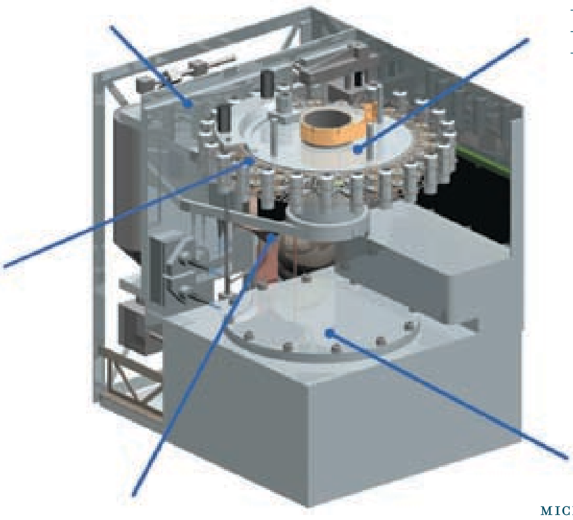
—STANLEY MILLER AND HAROLD UREY, IN *SCIENCE*, JULY 31, 1959

While Miller and Urey's timescale was, in hindsight, a bit optimistic, they did identify an enduring and compelling scientific question, one that continues to motivate us a half-century later. The quest to determine whether life ever existed, or still exists, on planets other than Earth will be the central focus of several missions planned by both NASA and the European Space Agency (ESA) in the next decade.

Definitive evidence for the presence of extant or extinct life on other planets requires detection and characterization of organic biomarker molecules at trace concentration levels. The technology for a new class of instruments capable of performing these tasks *in situ* is being developed at MDL. These instruments rely on special microfluidic components capable of withstanding the harsh space environment, and will integrate target molecule extraction methods with lab-on-a-chip analyzers for the separation, detection, and characterization of biomolecules at sensitivity levels approaching one molecule in a gram of solid sample.

One such instrument is the Mars Organic and Oxidant Detector, now named Urey in recognition of Harold Urey's seminal contributions to the sciences of cosmochemistry, geochemistry, and the origin of life. The Urey instrument, under development for the 2013 ExoMars mission, will be the first microfluidic instrument to explore the chemistry of an extraterrestrial environment, and will perform direct astrobiological investigations on the Martian surface. Urey has the potential of performing the first successful detection of bio-organic compounds on Mars. Urey has a demonstrated detection sensitivity of better than 0.01 parts per trillion of primary amine-containing compounds, using fluorescamine as the labeling reagent. Field tests in the Atacama Desert of Chile and at a sulfate mineral-rich site in California have demonstrated the robustness of Urey's analytical approach.

Optical microscope image of a single Teflon microfluidic valve.



Design concept for Urey instrument.

Current Projects

The Urey organic detector consists of three subsystems under development at MDL: the Subcritical Water Extractor (SCWE), the Mars Organic Detector (MOD), and the Micro-Capillary Electrophoresis instrument (µ-CE). The SCWE handles the task of getting any organic compounds out of each powdered sample. A two-stage extraction procedure first liberates organic compounds from the soil using high-temperature, high-pressure water (SCWE). Target compounds are then isolated and concentrated via sublimation onto a cold finger (MOD). The system is configured around the µ-CE instrument that separates and analyzes fluorescamine-labeled primary amine compounds and naturally fluorescent polycyclic aromatic hydrocarbons. The micro-capillary electrophoresis separates different types of organic compounds from one another for identification, including especially the separation of mirror-image amino acids from each other — key information for life detection.

More information on the Urey instrument and its science goals may be found at http://mars.jpl.nasa.gov/spotlight/20070209.html.

2007 Highlights

1. THE LAB-ON-A-CHIP COMPONENTS FOR UREY, in particular on-chip valves and pumps, have been under continued development at the MDL over the past year.

2. FABRICATION OF COMPONENTS: A host of fabrication technologies have been developed at MDL for bonding flexible fluorocarbon membrane materials to hard glass microfabricated wafers that are robust enough to survive the extremely harsh thermal conditions required for spaceflight and deployment on Mars.

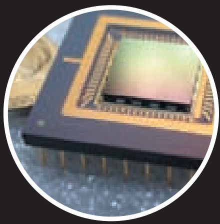
3. CE DEMONSTRATION: we have fabricated and demonstrated the first integrated JPL prototype CE instrument, involving valving and pumping, fluidic sample routing, chromatographic separation, and fluorescence detection.

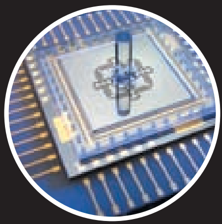
Conceptual presentation of ExoMars rover. The ExoMars aim is to characterize the biological environment on Mars in preparation for human exploration.

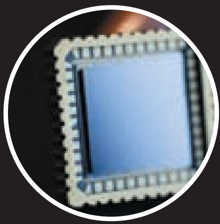
MDL 07 ANNUAL REPORT

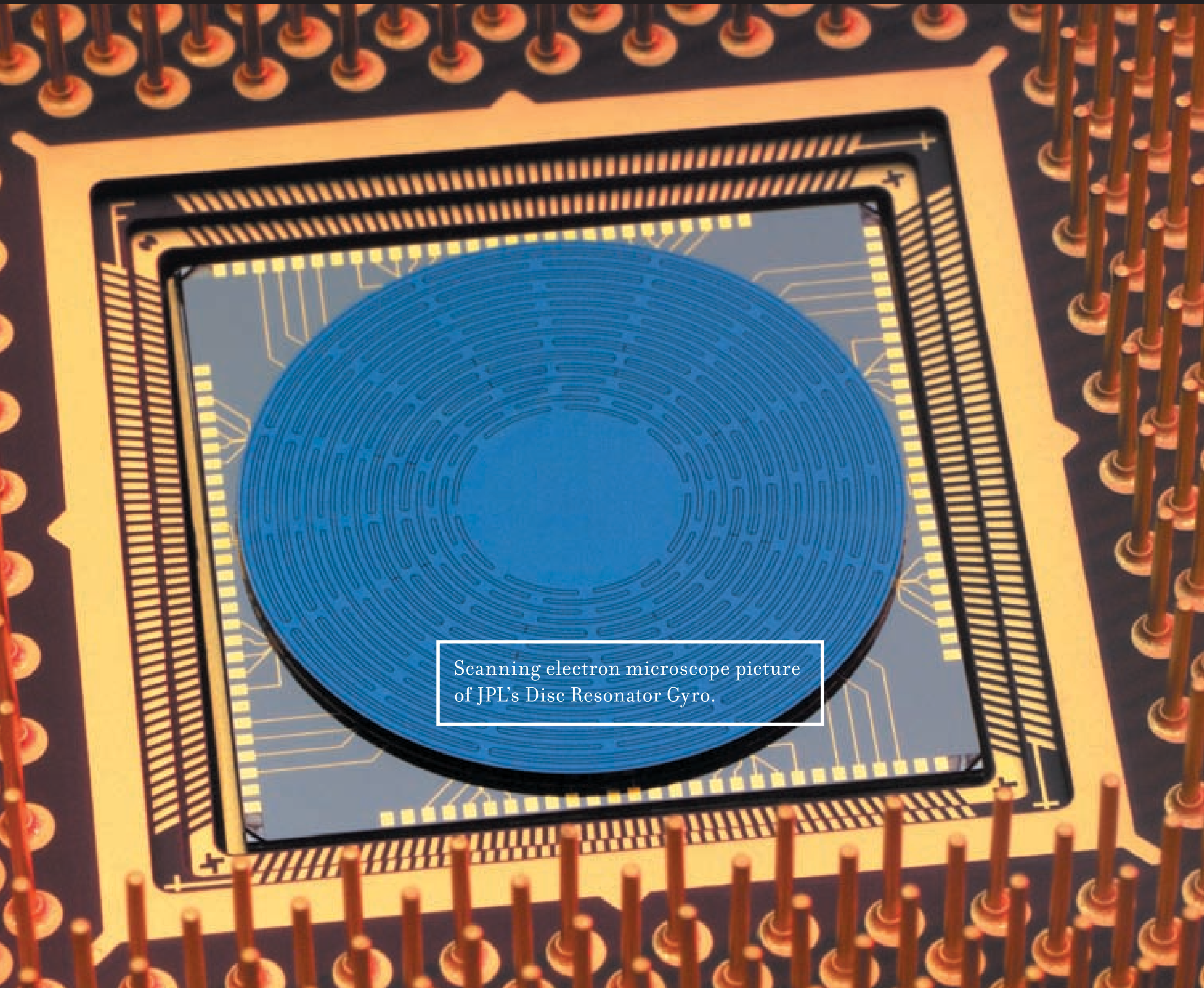
Microdevices Laboratory

{Micromachined Disc Resonator Gyroscope}









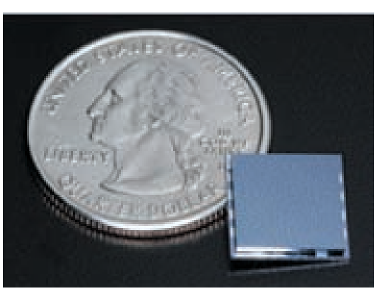
Scanning electron microscope picture of JPL's Disc Resonator Gyro.

Although most JPLers would associate gyroscopes with navigation on Earth and in space, gyroscopes now have myriad other uses including automobile safety (rollover detection/prevention and anti-skid control), video games (Wii)™, image stabilization in digital cameras, and stabilization for the Segway transporter. Gyroscope technologies that have flown or will be flown on JPL/NASA missions include ring laser gyros (used on Phoenix and MSL), fiber optic gyros (used on MER and DS1), spinning mass gyros (used on Chandra and Spitzer) and vibratory gyros such as the hemispherical resonator gyro (used on Cassini and GALEX). MEMS gyros are a type of vibratory gyro, but are far smaller, consume less power, and are much less expensive because they can be batch fabricated in large volumes. However, historically, they have tended to be much less accurate. The current JPL disc resonator gyroscope (DRG) design is the result of a long-term effort over more than a decade, aimed at achieving performance comparable optical gyroscopes while retaining all the advantages of MEMS devices.

An exploded view of the DRG is illustrated in the figure below. Multiple narrow periodic slot segments etched through a planar wafer disc (blue) simultaneously define a unique in-plane resonator structure and a matching large-area electrode array (green) for capacitive sense and actuation with very high area efficiency.

A sinusoidal voltage applied to one set of electrodes drives the ring structure into a quadrupole mode of oscillation. The Coriolis effect couples this energy into the second, degenerate, quadrupole mode of the two-dimensional ring structure. A feedback voltage signal applied to a second set of electrodes (rotated from the first by 45 deg) suppresses the motion of the second mode, and the value of the feedback voltage is a measure of the rotation rate.

The superior performance of the DRG is primarily due to its unique JPL-patented design.



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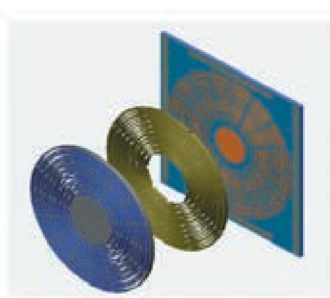

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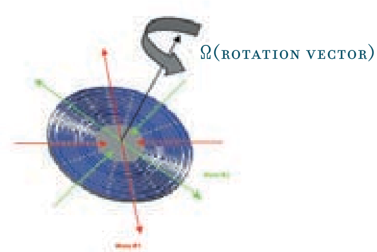
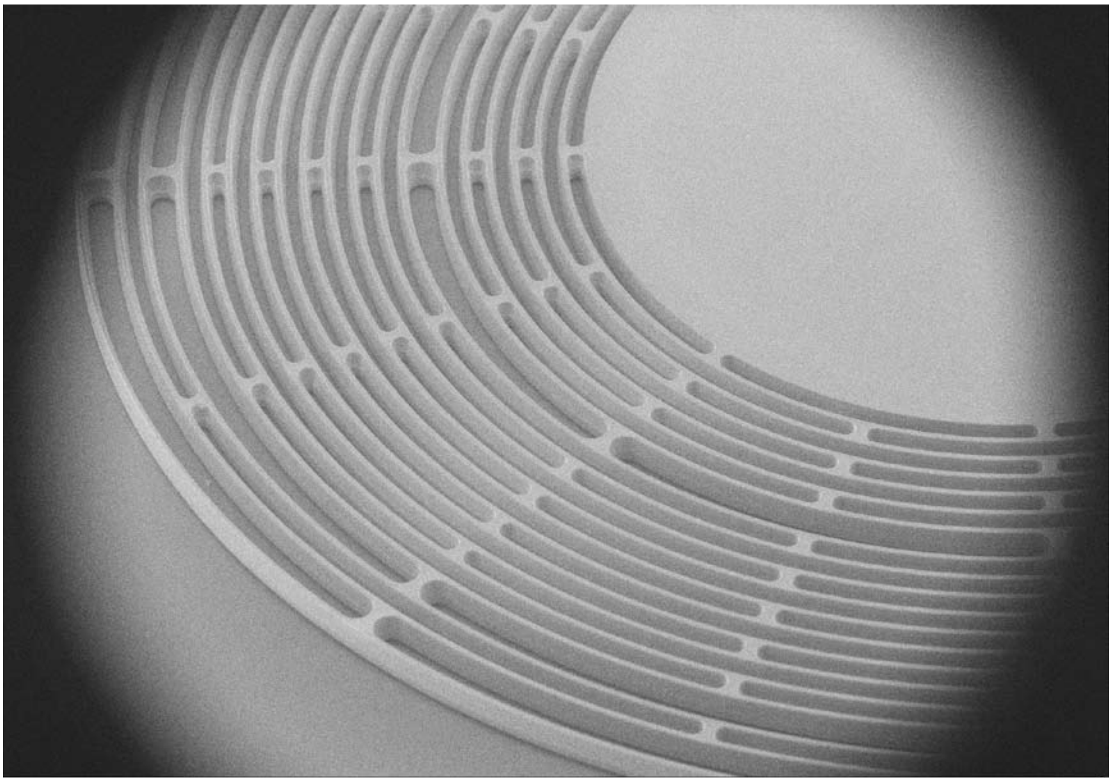


c-

Above: (a) Single-axis disc resonator gyroscope (DRG). (b) Exploded view of DRG. (c) Degenerate oscillation modes of resonator ring structure (colored arrows indicate instantaneous direction of motion of mass elements of the ring structure).



Close-up view of a quartz DRG resonator. Shown are the trenches that define the resonator structure and electrodes.

The co-etched resonator/electrode structure of the DRG efficiently maximizes use of the area of the sensor to increase sensing capacitance, and thus also increases the signal-to-noise ratio; also, the axially symmetric design and nodal support ensure minimal coupling to package stresses. Simple load analysis has verified that the device should survive acceleration loads in excess of 1000 g. These benefits have been proven with a DRG made using silicon, which has demonstrated ≥10x reduction in the in-run bias instability over state-of-the-art commercial MEMS devices.

Current Projects

COMMERCIAL DRG: This industry-funded effort has been focused on the streamlining of the silicon DRG fabrication process for yield improvement, the development of inexpensive batch vacuum packaging techniques, and the development of digital electronics.

HIGH-PERFORMANCE DRG: Research is being conducted on the methodologies for raising the performance of the DRG to navigation grade. The focus has been on increasing the sensitivity of the device by raising the mechanical quality factor of the resonant element. Subsequent phases will concentrate on reduction of size and power of the electronics through the development of an ASIC, and the 3-axis integration of DRGs with accelerometers to form a compact inertial measurement unit.

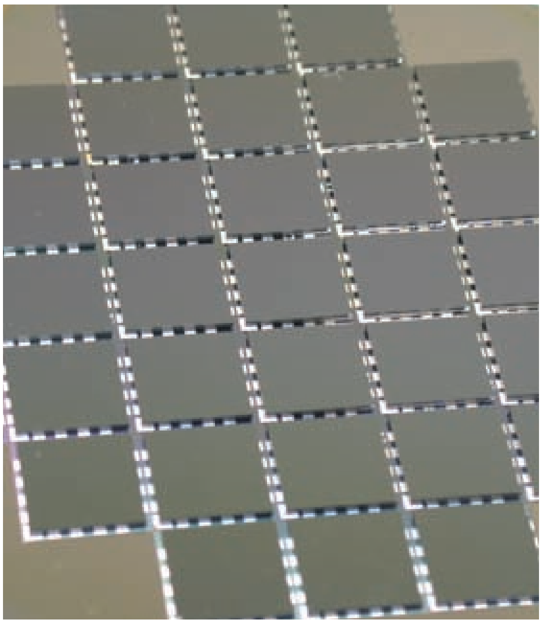
2007 Highlights

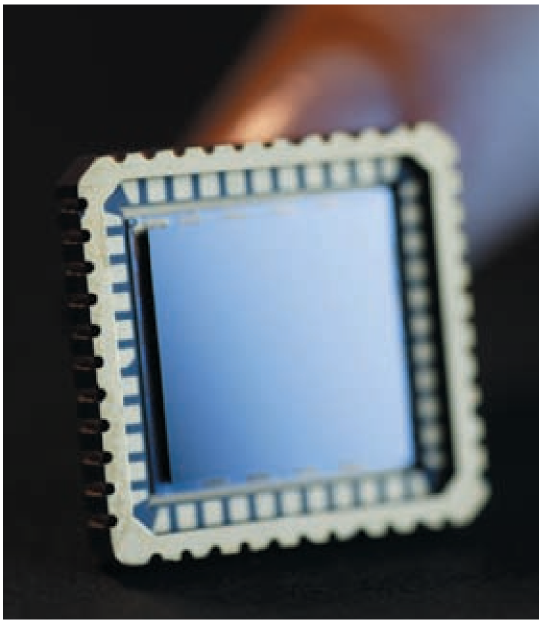
COMMERCIAL DRG: Commercialization rights for the DRG were licensed by the startup company Sensors In Motion (SIM) in 2006. A streamlined DRG fabrication process was developed and transferred to SIM for the fabrication of the first commercial prototypes. Also, a vacuum packaging process for the DRG has been developed that has demonstrated nearly two orders of magnitude lower internal pressure over similar processes used in industry. Finally, FPGA-based digital electronics that can be used with any type of MEMS gyroscope, not just the DRG, have been developed.

HIGH-PERFORMANCE DRG: Materials other than silicon for DRG construction were investigated, involving the development of micromachining techniques and methodologies for the high-aspect-ratio etch of glasses. As a result, the quality factor of the resonating element of the DRG has been raised by >50x, allowing much greater device sensitivity. All aspects of the fabrication and assembly of the sensor, with the exception of the deep trench, high-aspect-ratio oxide etch step, are performed at MDL. These new materials and the associated micromachining techniques can also be utilized to substantially improve the performance of any type of resonant vibratory MEMS device.

Funding agencies for FY2007 included DARPA, the U.S. Army, and Sensors in Motion (SIM). The work for DARPA has been a collaborative effort among JPL, the Boeing Co., HRL Laboratories, UCLA, and Worcester Polytechnic Institute (WPI).

Left: Wafer of silicon DRGs prior to dicing. Right: DRG mounted in leadless chip carrier (LCC) for vacuum packaging.

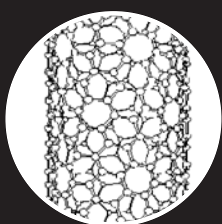


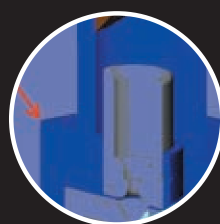
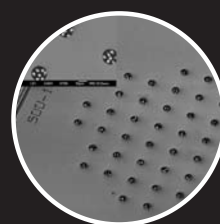


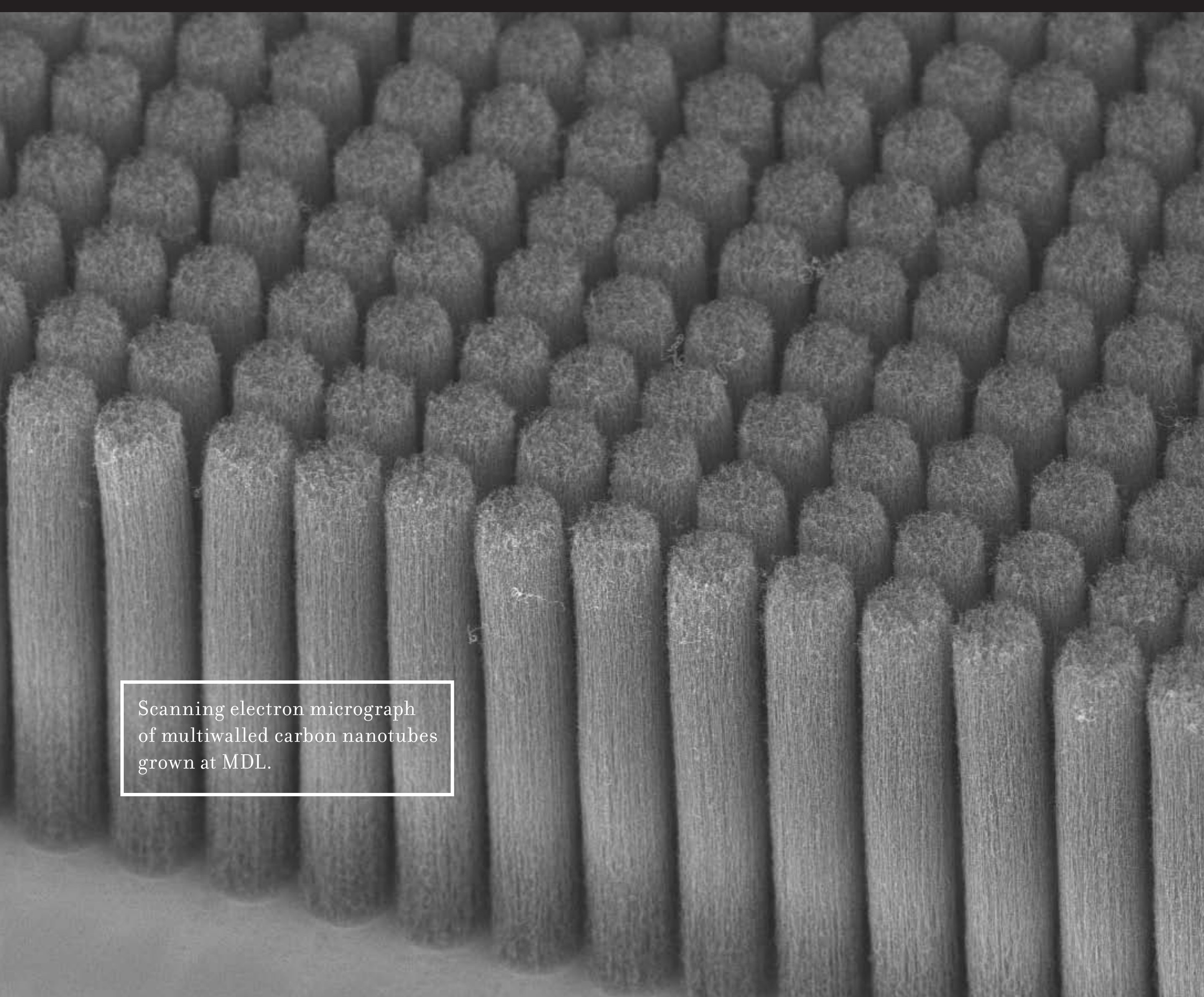
MDL
Microdevices Laboratory

07 ANNUAL REPORT

{Applied Nanotechnology: Field Emitters and Related Miniature Instruments}



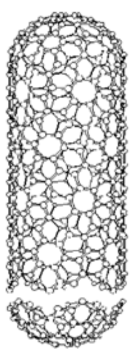


Scanning electron micrograph of multiwalled carbon nanotubes grown at MDL.

The discovery of carbon nanotubes (CNTs) in 1991 by Dr. Ijima (Japan) generated enormous interest and stimulated a broad range of activity in the scientific and technical communities. The potential applications of CNTs are vast, ranging from electronic devices to flat-panel displays.* At MDL, CNTs are being investigated primarily for a variety of miniaturized instruments that are much smaller than their conventional laboratory counterparts, allowing them to be considered for spacecraft payloads. CNTs are intriguing tubular structures of carbon (see image below) that span a diameter range of one to a few tens of nanometers. They can be grown to different heights; the current height record, held by Ijima, stands at 25 mm, and corresponds to a huge geometrical aspect ratio around 10^6. This provides a hint that CNTs have remarkable material properties. For example, their tensile strength is known to be stronger than that of steel, which is why they are mentioned as the material to make space elevators — a concept developed by Arthur C. Clarke in one of his novels. CNTs can be semiconducting, which makes them interesting from a high-density electronics point of view, and their dimensions are conducive for high-performance nanoelectromechanical elements, high-sensitivity molecular detectors, and efficient field emitters.

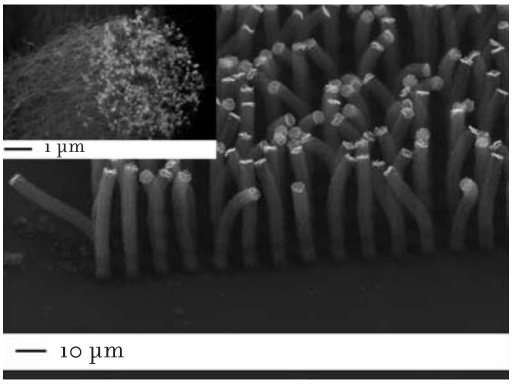
CNT work was started at MDL in 2000–2001 by Dr. Brian Hunt, and was initially focused on the development of high-sensitivity CNT-based chemical sensors for planetary *in situ* applications as well as high-frequency CNT nanoresonators for defense applications. However, the excellent field emission properties of CNTs motivated an expanded research effort to develop cold electron sources, leading to a pipeline of projects involving miniature instruments and vacuum microelectronics, including future NASA missions (Mars, Venus, Titan, and Europa), DoD, commercial, and medical applications.

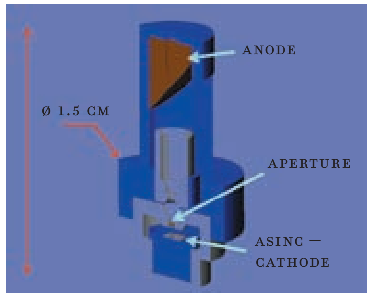
Field emission works on the principle of extracting electrons from materials into vacuum by the application of an electric field. Because the electric field is significantly enhanced at sharp tips, such structures readily emit electrons at very low voltages. This is a room-temperature process. CNTs naturally offer very sharp tips for field emission, and additionally, they are very robust to poor vacuums. CNTs are therefore an attractive choice for miniaturized instruments that require field emitters as electron sources.



Tubular structure of a carbon nanotube. The structure basically looks like a hexagonal wire mesh sheet that has been wrapped around to form a tube.

*For more information, see Baughman et al., *Science* 297, 787, 2002.





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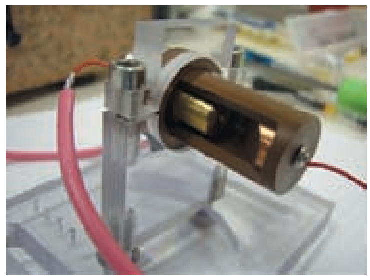


b.

Above left: JPL-developed CNT bundle array architecture that has resulted in high current densities. Each bundle has many CNTs. Above right: (a) Exploded drawing of the miniature X-ray tube using ASINC, (b) Photograph of the copper X-ray tube as fabricated.

Current Projects

1. APPLICATION-SPECIFIC ELECTRODE-INTEGRATED NANOTUBE CATHODES (ASINCs): JPL has developed an array architecture (see image above) of CNT bundles that produces high current densities at low applied fields. Typically, we have measured 10 to 20 amperes/cm^2 at 5 to 10 V/μm field. These structures can be monolithically integrated with electrodes to extract, accelerate, and focus electrons as required by an application. Hence, these integrated structures are called Application-Specific Electrode-Integrated Nanotube Cathodes or ASINCs.

2. MINIATURE X-RAY TUBES FOR FUTURE MINERALOGY INSTRUMENTS: ASINCs make possible the development of efficient, lower-voltage compact X-ray tubes (see right image above) for mineralogy applications (CheMin-type XRD/XRF instruments). By bombarding a metal target (such as cobalt or copper) with energetic electrons, X-rays necessary for mineralogy are produced. The high current density and room temperature operation of ASINCs allow lower power consumption (1 to 2 milliwatt range), less challenging power supplies (15–20 kV), and higher data collection rates (integration times of a few minutes).

3. MASS IONIZERS FOR MINIATURE MASS SPECTROMETER: Using a specific emitter arrangement, we are able to make gas ionization sources for a miniature quadrupole mass spectrometer for planetary atmospheric gas analysis and for astronaut health monitoring. Employing ASINCs saves power consumption by two orders of magnitude while enhancing the signal strength by two orders of magnitude compared to ionizers based on traditional thermionic cathodes.

4. VACUUM MICRO-TUBE AMPLIFIERS AND "DIGITAL" VACUUM MICROELECTRONICS: Two new projects, both funded by DARPA, will soon be starting. The first

project will be to develop a submillimeter-wave source with high output power using a CNT-based vacuum microtube amplifier. The second project is to develop the concept of CNT-based "digital" vacuum microelectronics for extreme environment applications. Both projects use tailored CNT field emitters for operation.

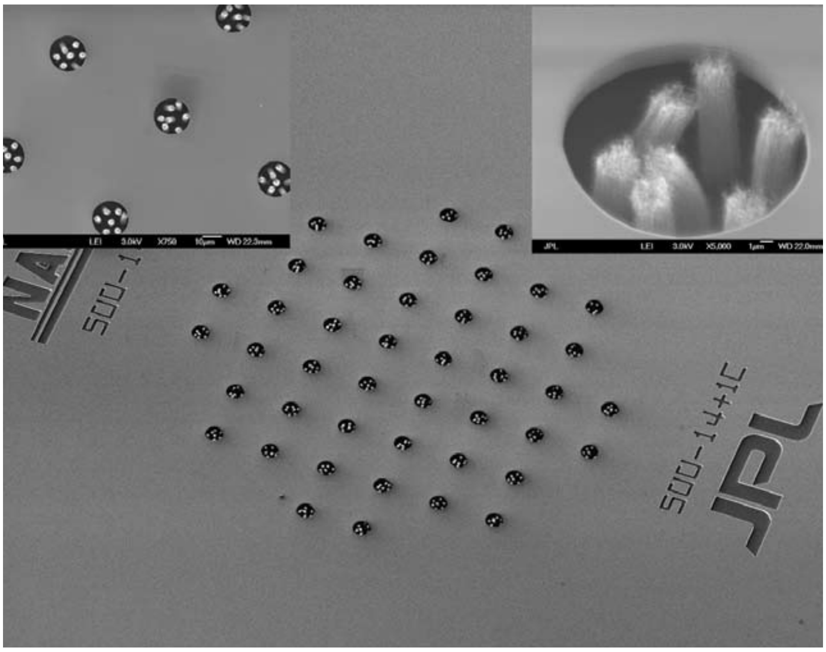
2007 Highlights

ASINCs: The emission density was increased to >10 A/cm^2 on a routine basis from CNT bundle array samples that occupied a circular area of 100 μm diameter. Using a new double silicon-on-insulator (SOI) process, monolithic dual-electrode integrated ASINCs have been developed (see image below) and have been tested as triodes.

MINIATURE X-RAY TUBES FOR FUTURE MINERALOGY INSTRUMENTS: A miniature X-ray tube (~5 cm long) with copper and cobalt anodes was made and tested using ASINCs. A flux of 10^3–10^4 photons/s was measured through a 1-mm-diameter aperture using an accelerating voltage of 15 kV with 10 μA of current. This experiment was conducted in 10^{-5} torr vacuum.

MASS IONIZERS FOR MINIATURE MASS SPECTROMETER: ASINC-based ionization sources for mass spectrometers were successfully produced. These sources are currently being tested in a flight-equivalent module of a quadrupole mass spectrometer. The total current requirement from these sources for mass ionization is only 1 mA.

SEM micrograph showing monolithically gate-integrated CNTs.



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Appendix A: MDL Equipment Complement

MATERIAL DEPOSITION:
- Thermal Evaporators (8)
- 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)
- Chemical Vapor Deposition (CVD) Systems for doped and undoped amorphous Silicon (2)
- Plasma Enhanced Chemical Vapor Deposition (PECVD) for dielectrics
- Inductively Coupled Plasma (ICP) PECVD
- Atomic Layer Deposition (ALD) System
- Low-Pressure (LP) CVD (Tystar) 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 System
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  — Epi GEN III MBE (antimonide materials)
  — Riber MBE for UV CCD delta doping (silicon)
  — Riber Materials MBE (GaAs and GaN)
  — 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.
- CGA 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 (2)
- Yield Engineering System (YES) Reversal Oven
- Ovens, hotplates, and manual spinners

DRY ETCHING:
- Commonwealth IBE-80 Ion Mill
- Branson Plasma Asher
- Tepla PP300SA Microwave Plasma Asher

FLUORINE-BASED PLASMA ETCHING SYSTEMS:
- STS Deep Trench Reactive Ion Etcher (DRIE)
- Unaxis Shuttleline Load-Locked Fluorine ICP RIE

- Plasmaster RME-1200 Fluorine RIE
- Plasma Tech Fluorine RIE
- STJ RIE for superconductors
- Custom XeF_2 etcher

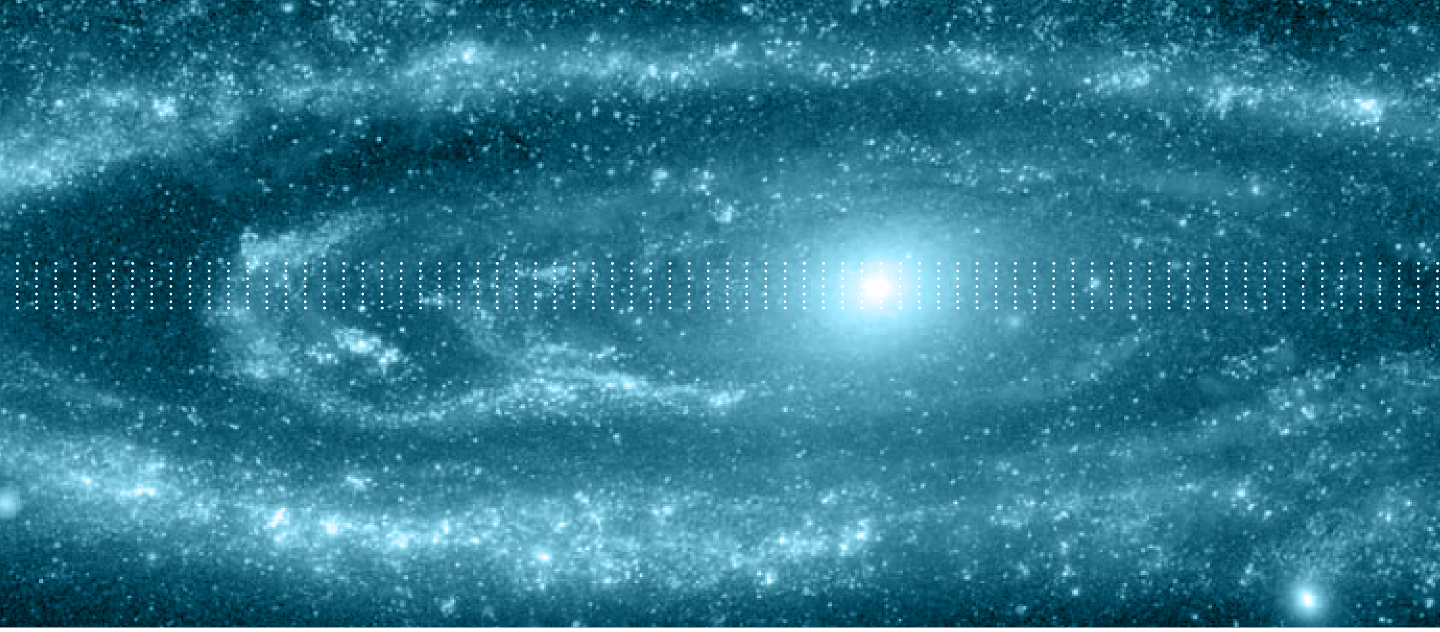
CHLORINE-BASED PLASMA ETCHING SYSTEMS:
- Unaxis Shuttleline Load-Locked Chlorine ICP RIE
- Chlorine Reactive Ion Etcher (RIE)
- ECR 770 Chlorine RIE ICP Chlorine RIE

WET ETCHING AND SAMPLE PREPARATION:
- RCA acid wet bench for 6-inch wafers
- Solvent wet processing benches (7)
- Rinser and dryer for masks and wafers
- Chemical hoods (7)
- Acid wet processing benches (7)
- Critical Point Dryer

SAMPLE PREPARATION:
- 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)
- 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
- JEOL JSM-6700 Field Emission SEM with EDX
- JEOL Field Emission SEM for NEMS
- Nikon Inspection Microscope with image capture
- Confocal Microscope
- Electrical Probes
- Parameter Analyzers
- 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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