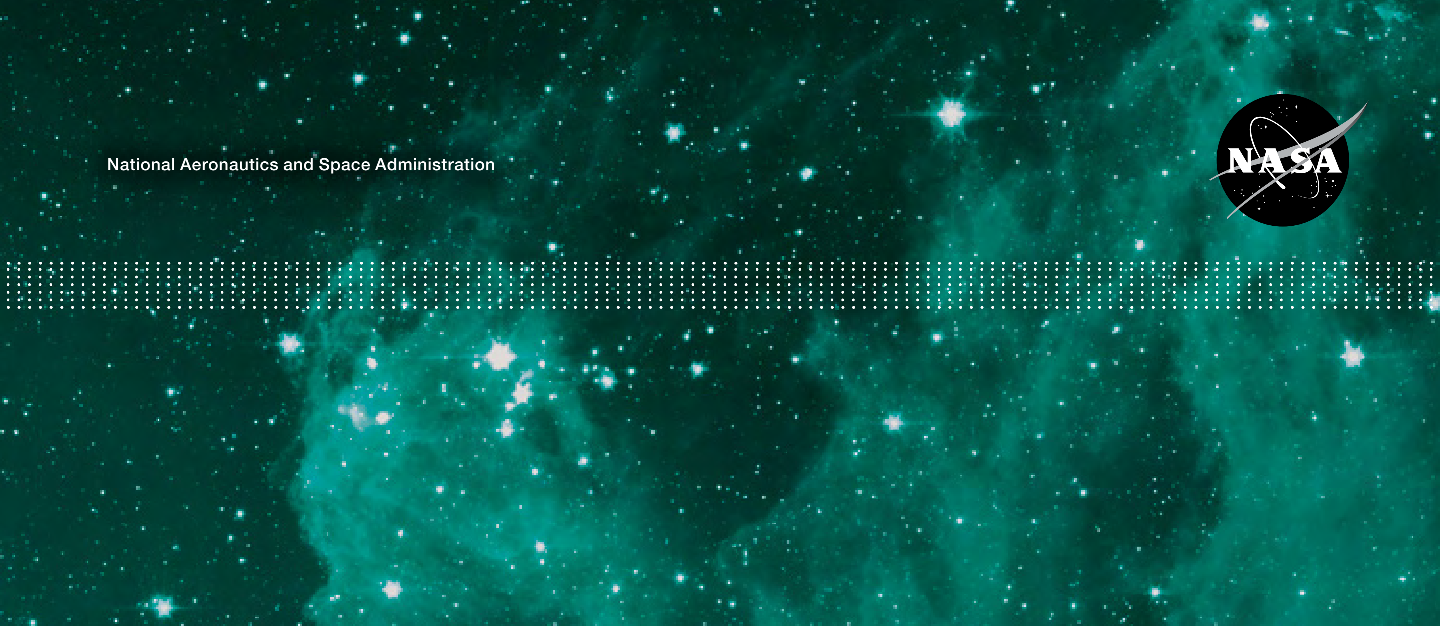
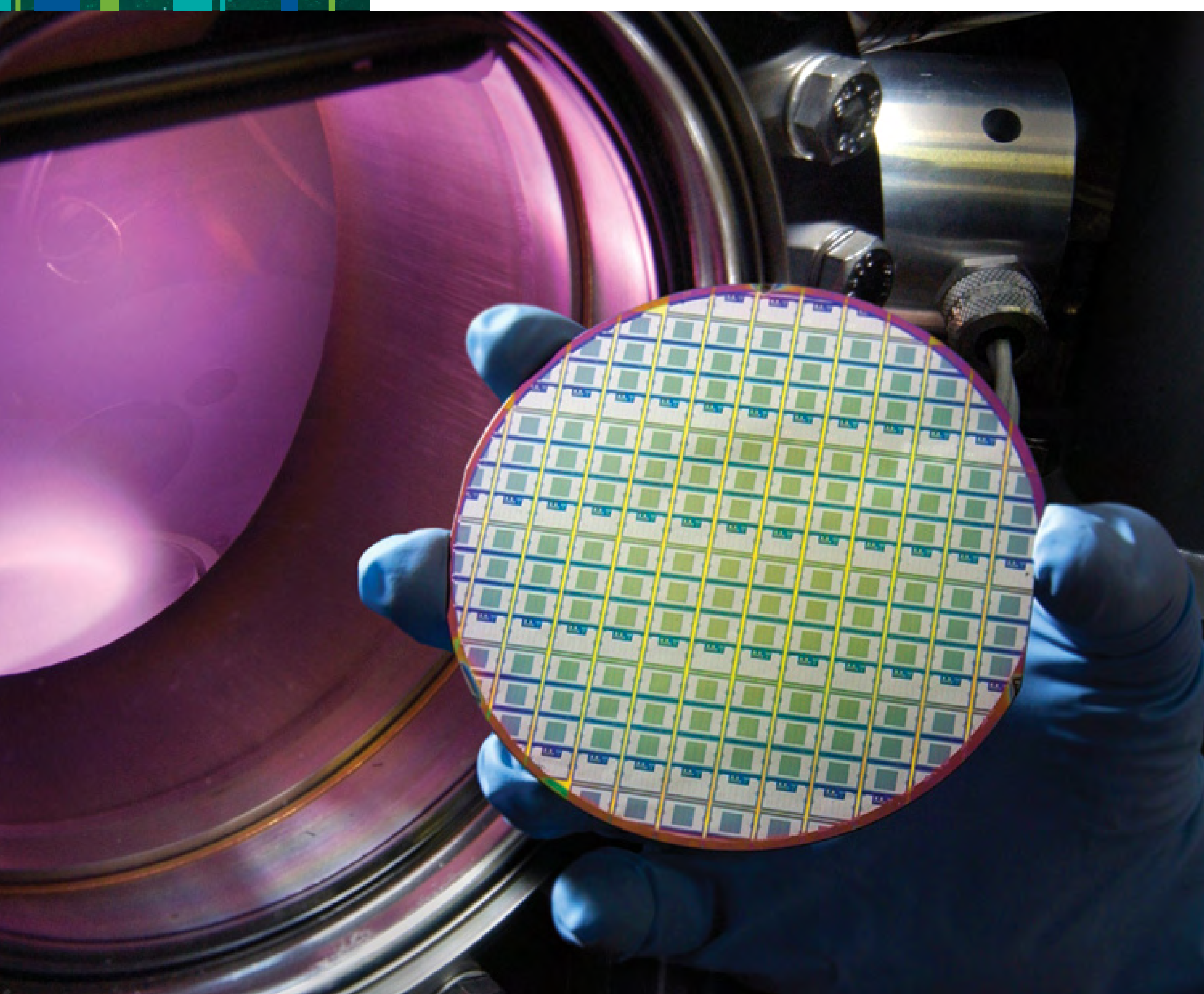
National Aeronautics and Space Administration



JET PROPULSION LABORATORY

MICRODEVICES LABORATORY

2008 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.


MICRODEVICES
LABORATORY

DIRECTOR'S LETTER

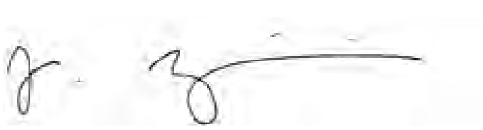
AT THE MICRODEVICES LABORATORY (MDL), WE SPEND A LOT OF TIME IMAGINING THE FUTURE. OUR PRIMARY GOAL IS TO DEVELOP TECHNOLOGIES AND DEVICES THAT WILL ENABLE OR ENHANCE SPACE MISSIONS OR INSTRUMENTS, SO WE THINK ABOUT WHAT CAPABILITIES WILL BE NEEDED FOR FUTURE MISSIONS, AND HOW WE MIGHT HELP DEVELOP THOSE.

This can be a very long process from start to finish, often decades, so patience and persistence are essential. To stay the course, it is occasionally helpful to look backwards into the past, to remind ourselves that success is indeed possible!

In May 2009, the European Space Agency (ESA) is planning a simultaneous launch of two space observatories: Herschel and Planck. Planck will study the cosmic microwave background — the 2.7 K blackbody radiation produced just 300,000 years after the Big Bang, and a treasure trove of information about the Universe — by making exquisitely sensitive, high-resolution maps covering the entire sky. Meanwhile, Herschel will use its 3.5 meter far-infrared telescope to pick up the story of the Universe from around 1 billion years to the present 13.7 billion years after the Big Bang, providing crucial information about the formation of stars and galaxies during this period. Of the five science instruments carried by Herschel and Planck, three rely on JPL/MDL technology for sensitive photon detection — the most critical function of each instrument, and one that dictates their scientific capability. The story of how MDL/JPL became involved in these missions dates back three decades and was recently revisited during a symposium held in honor of Prof. Tom Phillips (see pages 40-41).

On the evening of September 16, 2008, the MDL celebrated its 20-year anniversary at a dinner held at Caltech's Athenaeum. We were very fortunate to be joined by numerous friends and colleagues from JPL and Caltech, as well as our newly-formed MDL Visiting Committee. The Visiting Committee, twelve very distinguished scientists and engineers with wide-ranging expertise (see page 56), spent several days with us examining our work and our facilities. We very much appreciate their hard work and their thoughtful report with excellent suggestions, and we look forward to meeting with them again this year.

Thanks to the vision, commitment, and support of JPL management and especially the JPL Office of the Chief Scientist and Chief Technologist, the MDL remains healthy and active. Our vitality is documented by the 130 presentations given, nearly 60 journal papers published, and several international conferences hosted within the last year. I remain very excited about the work being carried out at MDL and our possibilities for the future.



Jonas Zmuidzinas
Director, JPL Microdevices Laboratory

DIVISION MANAGER'S STATEMENT

OUR MICRODEVICES LABORATORY IS NOW IN ITS 20TH YEAR OF OPERATION. DURING THE PAST YEAR WE HAVE COMPLETED NUMEROUS MILESTONES IN THE CONTINUED EVOLUTION OF THIS UNIQUE JPL CAPABILITY, MANY OF WHICH ARE DELINEATED IN THIS ANNUAL REPORT.

Our investments have been guided under the leadership of Professor Jonas Zmuidzinas, who has continued as Director of the MDL. A key investment this year augmented our molecular-beam epitaxy (MBE) capability in support of JPL's strategic needs in Astronomy and Astrophysics. We are now installing a new 8-inch silicon MBE machine in MDL that will enable our efforts in large-format detector arrays.

With a strategic view in mind, this year we have established a Visiting Committee (VC) for the MDL. In their first visit, the VC has provided us with an external perspective of the MDL, our capabilities, and our future plans. For the most part, they have reinforced our belief in the capabilities of the laboratory but have also provided insightful observations for our future that likely would not have been recognized looking inward, and for that we thank them and look forward to this year's meeting.

Organizationally, we also recognized that over the years the scientists and technologists who use the MDL's capabilities had become distributed across many organizations at JPL. Although this provided good alignment with specific observational capabilities, it caused the MDL to lose institutional focus and dilute its identity. We have realigned the organizational structure so that the vast majority of our innovators who require the capability of the MDL are now located in a single section within the Instruments and Science Data Systems Division. Although very early in this realignment, we have seen increased efficiency in operating the MDL by minimizing organizational interfaces, which has resulted in a modest reduction in operating costs.

As you will read in this Annual Report, it has been a busy and productive year for the MDL. In this 20th year of operation we look forward with high expectation to continued innovation and invention in our microdevice and nano technologies that will enable JPL to make unprecedented discoveries in pursuit of its prime mission, contributing in unique ways to projects of national interest and enabling tomorrow what we can only imagine today.

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

MDL's World-Class JEOL JBX-9300FS Electron-Beam Lithography System uses a focused beam of electrons to write patterns directly on wafers. This powerful capability allows MDL technologists to create atom-sized features as small as 4 nanometers.

INFRASTRUCTURE, OPERATIONS, AND CAPABILITIES

THE MICRODEVICES LABORATORY (MDL) AT THE JET PROPULSION LABORATORY (JPL) HAS A FIRST-RATE FABRICATION FACILITY, CONSTRUCTED IN THE LATE 1980s AND LOCATED IN A DEDICATED BUILDING ON THE JPL CAMPUS. THE HEART OF THE MDL IS A 13,000 SQUARE FOOT CLEANROOM THAT IS USED BY OVER 70 RESEARCH SCIENTISTS.

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 contamination and defects. 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.

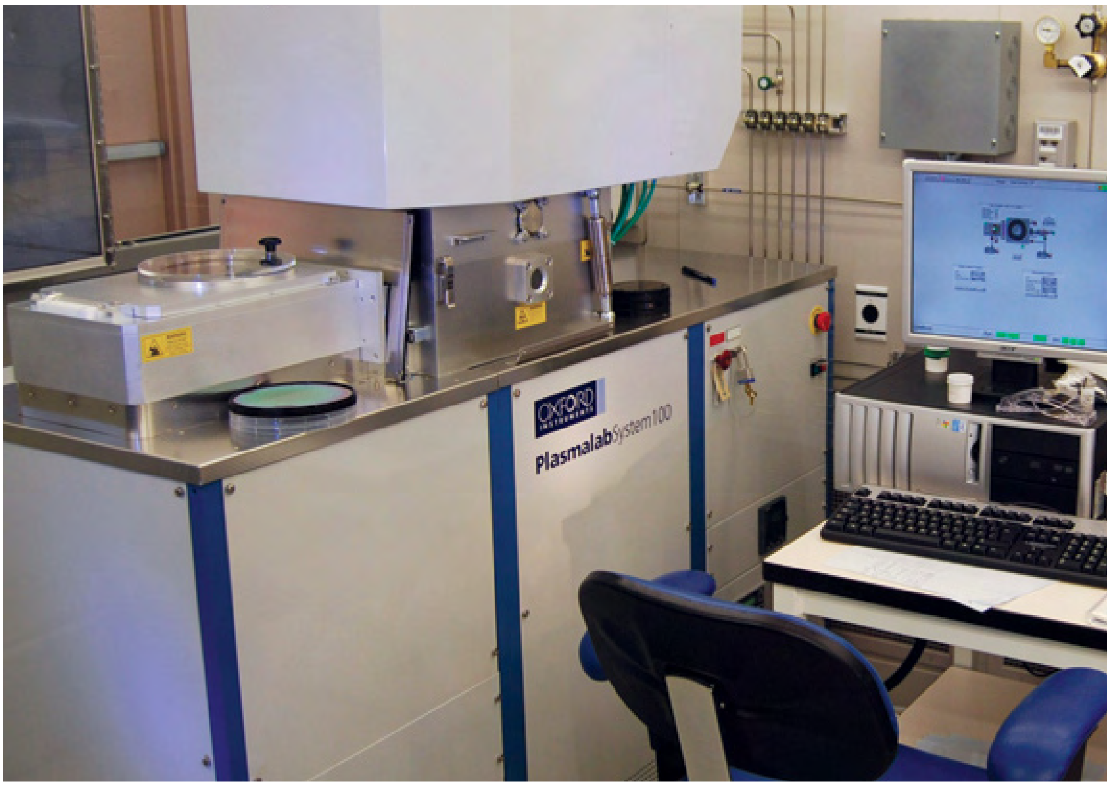
While industrial "fabs" are usually designed for mass production of devices using a standard process, the MDL is much more flexible, allowing research, development, and small-scale production of a very broad range of devices. The MDL functions as a multiuser and shared-equipment facility that is open to all JPL personnel. MDL access for users from outside institutions can also be arranged. The MDL Central Processing Group 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 supported by JPL institutional funds.

The MDL cleanroom is divided into various zones according to cleanliness standards, ranging from class 100,000 (International Organization for Standardization [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 ultraviolet (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, with some equipment dedicated to individual groups.

EQUIPMENT INVESTMENTS AND UPGRADES

Continuous investment in MDL's processing equipment is essential so that the equipment complement satisfies its unique space-application requirements. Since equipment for micro- and nano-fabrication develops at a very rapid pace, driven primarily by the semiconductor industry, and the timescale for obsolescence is short, the MDL is able to acquire previous-generation production equipment at substantial discounts. A good example is MDL's primary photolithography tool, the Canon EX3 deep-UV projection lithography system, which is capable of 0.25-μm resolution. However, because the MDL focuses on unique devices for space applications rather than the mass production of commodity

2008 HIGHLIGHTS



Oxford Instruments, Plasmalab System 100 Advanced ICP 380 HD PECVD.

chips, production equipment is not always suitable. MDL equipment is often smaller in scale, and may be custom built for specific requirements. The dedicated ultrahigh-vacuum (UHV) sputtering systems used to deposit superconducting films are examples of the latter category. Additional details on MDL's equipment complement can be found on page 54.

2008 HIGHLIGHTS

In 2008, MDL completed a management reorganization that placed all functions and operations under a single JPL line management chain. This reorganization has enabled a fundamental change in the way fees are collected and has allowed a 50% reduction in user fees to $25K/year for access to MDL's multimillion-dollar capabilities in 2009.

MDL continued to develop its capabilities for producing large detector arrays and processing 150-mm (6-inch) – diameter wafers through the installation of equipment purchased in 2007, as well as new investments. Of particular note were the installation of a custom-designed RCA wet cleaning bench to allow ultraclean wafer preparation while providing for reduced waste in the design; as well as new enhanced capabilities for precision etching and deposition over large wafer diameters by installing and making operational the Oxford Instruments Plasmalab 80 OpAL atomic layer deposition (ALD) system and several inductively coupled plasma (ICP) etchers and chemical vapor deposition (CVD) systems. Infrastructure and processing enhancements in the area of high density indium bump bonding over larger areas were also developed.

IN 2008, MDL COMPLETED A MANAGEMENT REORGANIZATION THAT PLACED ALL FUNCTIONS AND OPERATIONS UNDER A SINGLE JPL LINE MANAGEMENT CHAIN.

Custom-designed RCA wet cleaning bench with rinser dryer and waste-collection system providing ultraclean wafer preparation capabilities for 150-mm (6-inch)–diameter wafers.

Enhanced capabilities that were specified and purchased in 2008 for installation in 2009, include the following:

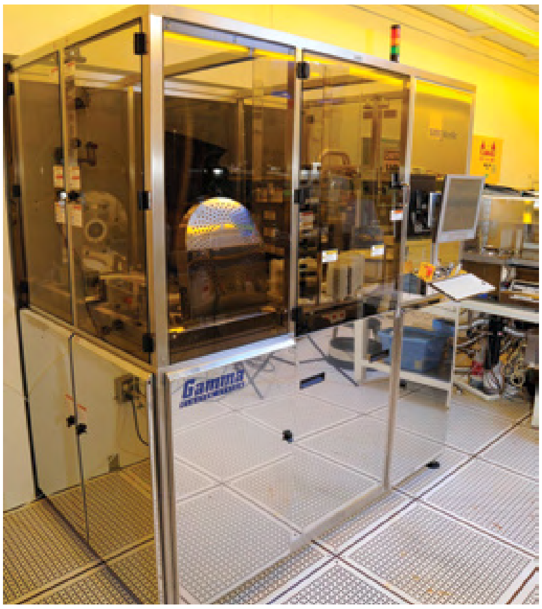
- Additional pumps and modules to fully populate the newly purchased Suss MicroTec Inc., Gamma microlithography 4-module cluster cassette-to-cassette spin/developer system. This capability allows automated precision photoresist processing of 75-mm (3-inch) to 200-mm (8-inch)–diameter wafers and provides for multiple chemistries to be utilized without cross-contamination issues.

- Silicon on insulator (SOI) upgrade for the existing STS deep-trench reactive ion etcher (DRIE). This capability prevents charging at the bottom of trench etches, thereby preventing notching at the base of the trenches. It also enhances the precision of the sidewall etches in general.

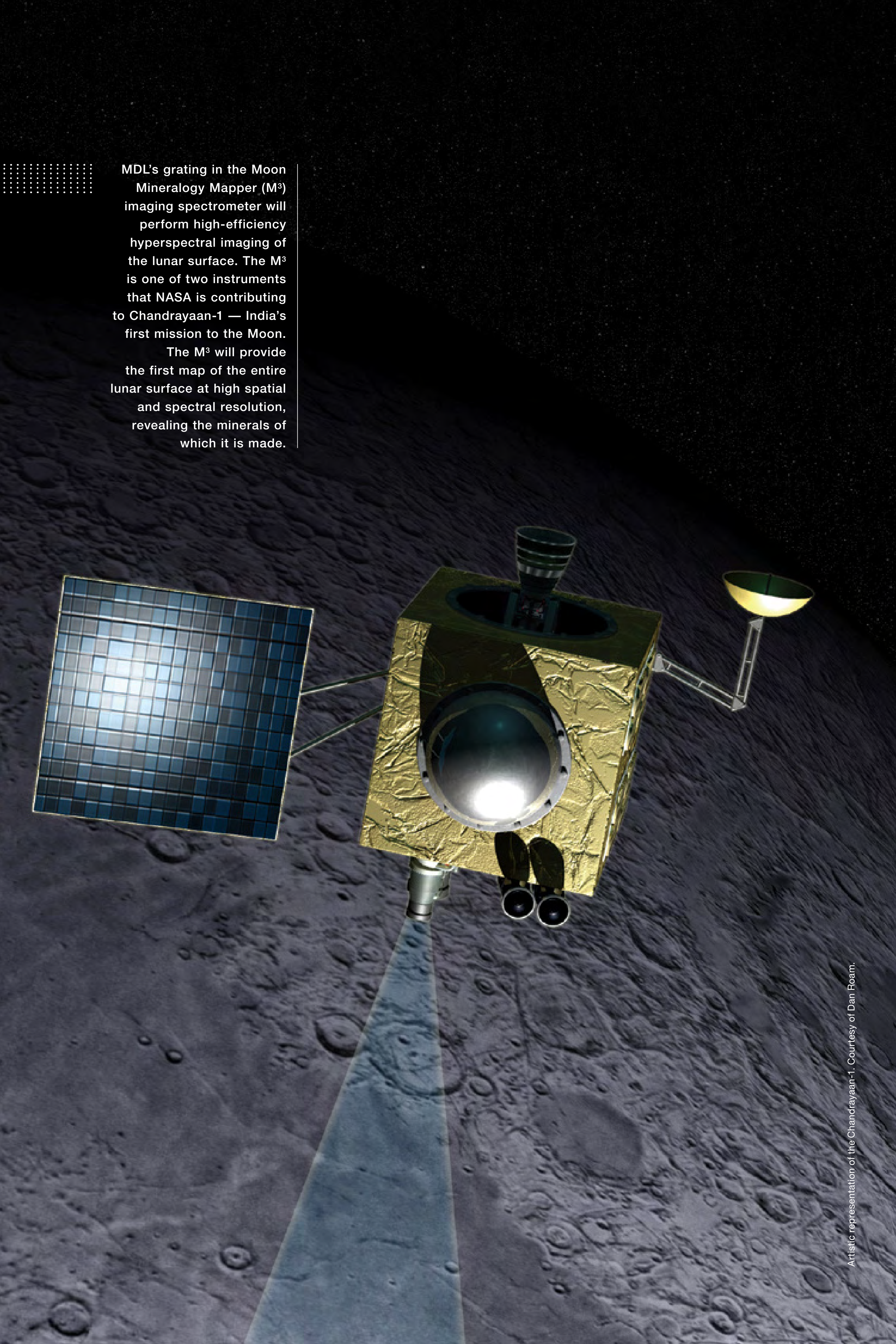
- Veeco GEN200 (8-Inch) silicon molecular-beam epitaxy (MBE) system. This system provides a means of producing delta-doped enhanced charge coupled device (CCD) imagers substantially larger than any previously available.

In addition to the equipment investments, several facility upgrades were also undertaken. These include fabrication and replacement of the dual blower wheels for MDL's inorganic exhaust system, and installation of variable-speed motors on MDL's six air handlers and 32 recirculation units (RCUs) for energy management.

Furthermore, a number of additional facility upgrades were initiated in 2008 for an early 2009 completion. The filters in the ceilings of the MDL cleanrooms are being replaced with next-generation high-efficiency particulate air (HEPA) filters, designated as ultra-low penetration air (ULPA) filters. Hot-water building feeds for MDL temperature and humidity control are being replaced, and a new enhanced process cooling water system for the equipment is being installed.



Fully populated Suss MicroTec Inc., gamma microlithography 4-module cluster cassette-to-cassette spin/developer system.



MDL's grating in the Moon Mineralogy Mapper (M^3) imaging spectrometer will perform high-efficiency hyperspectral imaging of the lunar surface. The M^3 is one of two instruments that NASA is contributing to Chandrayaan-1 — India's first mission to the Moon. The M^3 will provide the first map of the entire lunar surface at high spatial and spectral resolution, revealing the minerals of which it is made.

Artistic representation of the Chandrayaan-1. Courtesy of Dan Roam.

OPTICAL COMPONENTS

UNIQUE OPTICAL COMPONENTS FABRICATED BY ELECTRON-BEAM LITHOGRAPHY AT THE MICRODEVICES LABORATORY ENABLE JPL TO DEVELOP HIGH-PERFORMANCE INSTRUMENTS FOR NASA AND OTHER CUSTOMERS.

Frequently, MDL's components are key to the success of JPL instruments, such as diffraction gratings for imaging spectrometers. Key to the MDL's ability to fabricate high-performance optical components is our JEOL 9300FS electron-beam lithography system combined with in-house-developed software and techniques for exposing and developing analog surface relief profiles in e-beam resist.

Precise surface profiling can be accomplished with feature sizes on the order of the wavelength of light (ultraviolet through long-wave infrared), and thus highly efficient diffraction gratings, diffractive lenses, and more exotic optics such as computer-generated holograms can be fabricated. The 3D resist profiles can be coated with metal for reflective applications, left uncoated for transparent applications, or transfer-etched into the substrate material for extreme environment applications.

JPL has developed the ability to perform analog e-beam lithography not only on flat substrates, but on convex and concave substrates as well. This requires nonstandard calibration and control of our e-beam lithography tool, as well as precision substrate mounting and custom pattern preparation software. The need for nonflat lithography arises from compact, high-performance imaging spectrometer designs that require convex or concave diffraction gratings. Such spectrometers are able to measure the reflected spectra of many points on a planetary surface from a spaceborne, airborne, or in situ platform. The spectra can then be matched to library spectra to determine the material composition of the surface. In most cases, the wavelength range of interest covers multiple octaves (e.g., 400 to 2500 nm), requiring the grating to diffract efficiently over the entire range. We accomplish this by fabricating multiblaze gratings composed of areas that are blazed at different wavelengths. The blaze areas and wavelengths can be designed to tailor the spectral efficiency of the grating to compensate for poor detector sensitivity or illumination in certain regions of the spectrum.

JPL fabricated the dual-blaze gratings for CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) that is in orbit aboard Mars Reconnaissance Orbiter (NASA). We have also developed shaped-groove gratings that utilize the same groove depth everywhere, but with a groove shape that is computer optimized to produce the desired efficiency versus wavelength response. We used this approach to fabricate the grating for Moon Mineralogy Mapper (NASA) (tri-linear groove, 0.43 to 3.0 μm) that is currently orbiting the Moon aboard Chandrayaan-1 (Indian Space Research Organization).

CURRENT PROJECTS

DIFFRACTION GRATINGS

We continue to develop our diffraction grating fabrication technology to achieve new performance levels and extended wavelength ranges.

2008 Highlights: The Moon Mineralogy Mapper (M^3) spectrometer was successfully launched aboard India's Chandrayaan-1 on October 22, 2008, and is in orbit around the Moon. M^3 is operational and is transmitting spectra of the lunar surface.

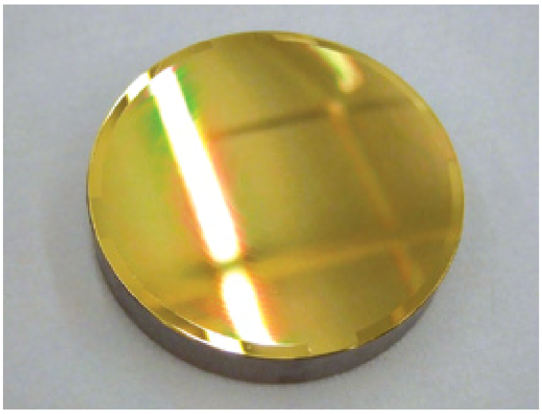
A low-polarization triple-blaze convex grating was fabricated and tested. The grating was designed to have tailored spectral efficiency from 400 to 2500 nm. Through groove shape optimization and specialized in-house coating, we demonstrated less than 2% polarization sensitivity over the critical 400–900-nm spectral region. Low-polarization sensitivity is critical for Earth-observing imaging spectrometers because our atmosphere polarizes the downwelling solar radiation to an unknown degree.

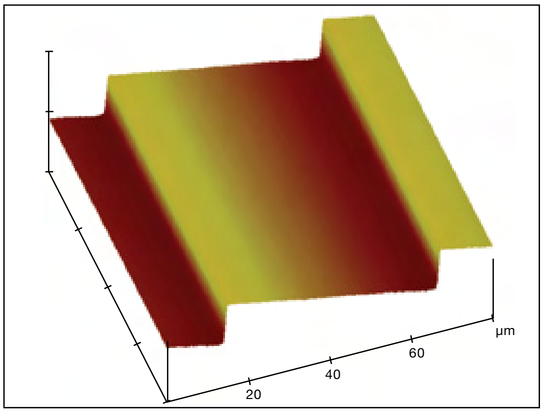
A long-wave infrared (LWIR, 8 to 12 μm) concave grating on a ZnSe diamond-turned substrate was fabricated. The grating enabled the successful demonstration of a LWIR Dyson imaging spectrometer. Dyson spectrometers are particularly well suited for LWIR operation due to their extremely compact size, allowing the entire spectrometer to be cooled to minimize the infrared background signal. In addition, Dyson spectrometers exhibit the same low image distortion as Offner spectrometers, but offer increased light throughput and reduced diffraction spread, which are especially important at long wavelengths.

We successfully developed a new process and fabricated a 2-inch-diameter convex grating for the 1.8 to 2.9 μm-wavelength band. We built a test setup and measured peak efficiency greater than 95% (>70% across the band) and ghosts less than 2×10^{-4} relative to the main diffraction order.

COMPUTED-TOMOGRAPHY IMAGING SPECTROMETER

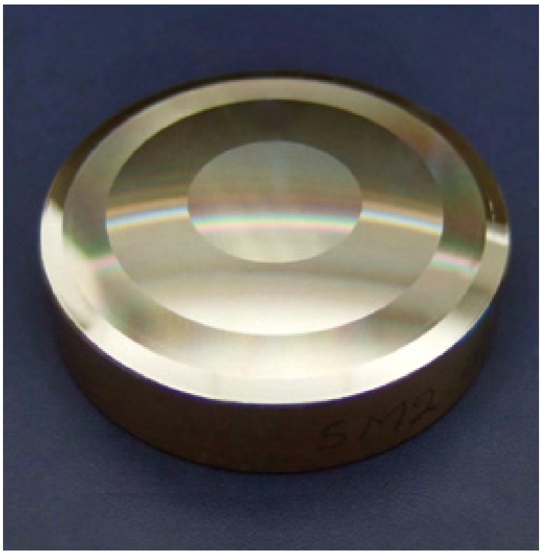
The computed-tomography imaging spectrometer (CTIS) enables snapshot imaging spectrometry of transient phenomena. It utilizes a two-dimensional computer-generated hologram grating to diffract light from a two-dimensional scene into multiple spectrally dispersed diffraction orders. A single focal plane array records all of the orders, and



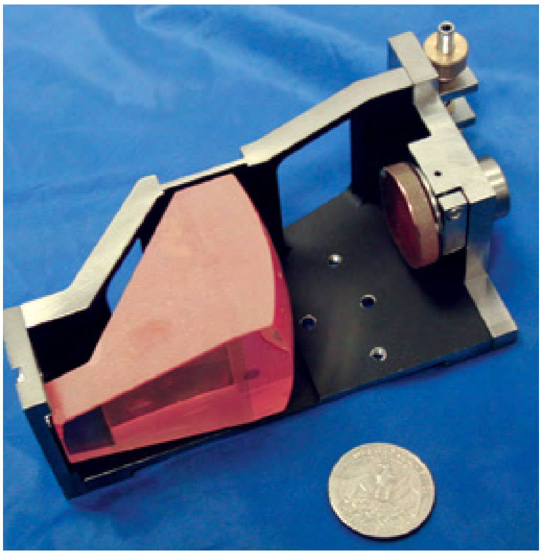


Left: Large-area (2-inch diameter) convex grating for infrared wavelengths of 1.8 to 2.9 μm.
Right: Atomic force microscope surface profile of the grating.

LOW-POLARIZATION SENSITIVITY IS CRITICAL FOR EARTH-OBSERVING IMAGING SPECTROMETERS BECAUSE OUR ATMOSPHERE POLARIZES THE DOWNWELLING SOLAR RADIATION TO AN UNKNOWN DEGREE.



Electron-beam fabricated triple-blaze convex grating for 400 to 2500 nm with low-polarization sensitivity. Each annular-shaped area is blazed for a different wavelength.



Long-wave infrared (8 to 12 micron) Dyson imaging spectrometer utilizing e-beam fabricated concave blazed grating (right side).

each recorded frame can be tomographically reconstructed to yield the spectra from all pixels within the scene.

2008 Highlights: We have fabricated and tested a reflective Offner CTIS that utilizes an e-beam fabricated convex 2D computer-generated hologram grating and a custom InGaAs focal plane array for 1- to 5-μm wavelength operation.

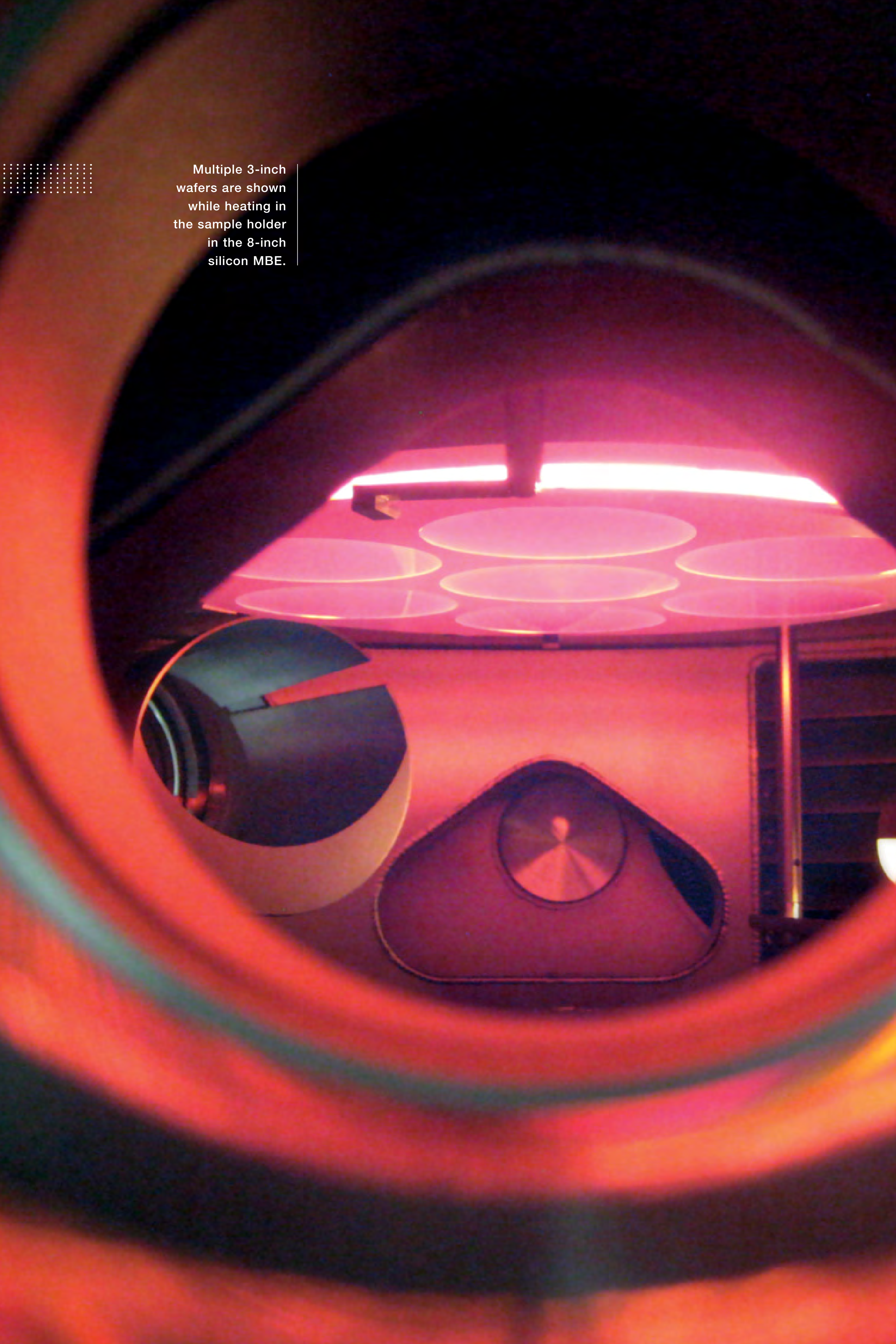
DIFFRACTIVE OPTICS

We are involved in a number of projects that make use of our high-resolution diffractive optics capabilities.

2008 Highlights:
Coronagraph occulting masks and shaped pupils. We have fabricated a number of binary half-tone and shaped-metal occulting masks for Terrestrial Planet Finder and James Webb Space Telescope (JWST) NIRCam coronagraphs. MDL has been selected to fabricate the flight occulting masks for the JWST NIRCam coronagraph.

Fluid flow sensor optics. In collaboration with Measurement Science Enterprise, we are designing and fabricating diffractive optical elements (DOEs) that enable noninvasive fluid flow sensors. The DOEs produce structured light patterns in the fluid, and particles scatter light to a detector, allowing determination of flow parameters.

Vortex phase masks. We fabricated an analog-relief vortex phase mask for Prof. Grover Schwartzlander (University of Arizona), and he and his students used it to demonstrate an astronomical optical vortex coronagraph by suppressing the light of the primary star in the resolvable binary system Cor Caroli.



Multiple 3-inch wafers are shown while heating in the sample holder in the 8-inch silicon MBE.

ADVANCED UV-VISIBLE-NIR DETECTORS

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. THESE TECHNIQUES ARE APPLIED TO A VARIETY OF MATERIAL SYSTEMS FOR CREATING UV TO IR IMAGERS.

One of the longest-standing problems in scientific imaging technology concerns architectural limitations on solid-state detector efficiency and spectral range. All solid-state imaging detectors including both complementary metal–oxide–semiconductor (CMOS) and charge-coupled devices (CCD) function by measuring electrons and holes generated by light incident on a semiconductor. Electrode structures are needed to manipulate and measure photogenerated charge, but at the same time scattering and absorption in the electrodes limit detector efficiency and spectral range. Ultraviolet light, for example, cannot be detected at all, and blue light is severely attenuated. Even at longer wavelengths, detector efficiency and resolution are compromised by the electrodes. These architectural limitations are more severe for CMOS detectors, which suffer from a higher metal content of the electrodes and a lower intrinsic fill factor. Regardless of the charge-collection architecture, i.e., CCD, CMOS, or P-I-N hybrids, all silicon imagers will require back illumination to achieve optimum performance. As a result, virtually all modern scientific CCDs are designed for back-illumination, while back-illuminated scientific CMOS detectors are still in their infancy.

In the 1980s, when CCD detectors were still a relatively recent innovation, JPL had already established itself as a world leader in solid-state scientific imaging arrays. JPL scientists and engineers pioneered the development of back-illuminated CCDs. They discovered that back-illumination can overcome the limitations of front-surface illumination, but high efficiency, stability, and uniformity can only be achieved with suitable processes for thinning and back-surface passivation. Various approaches to surface passivation have been tried, including UV-flood, flash-gates, and ion implantation/anneal, but none of these can match the successes of MDL's delta-doping technology, which was developed in the early 1990s. Delta-doped detectors exhibit 100% internal quantum efficiency throughout the visible and ultraviolet spectrum, exhibit exceptional uniformity with no measurable hysteresis, and have demonstrated very low dark current. Moreover, delta-doping enables biasing of the detector structure to achieve full depletion. Compared to ion implantation and post annealing processes used by the leading manufacturers of scientific CCDs for space flight, delta-doping provides higher quantum efficiency and much better uniformity. Unlike ion-implantation and all other back surface passivation processes, delta-doping provides absolutely stable response across the entire visible and ultraviolet spectrum, enabling the absolute photometric stability required for many scientific imaging applications.

CURRENT PROJECTS

HIGH-THROUGHPUT PROCESSES FOR HIGH-PERFORMANCE SILICON IMAGERS IN UV-NIR

Silicon imagers continue to be the best detectors for the ultraviolet–near-infrared (UV-NIR) spectral range. To achieve highest performance, it is necessary to operate silicon imagers in a back-illuminated configuration. If this back surface silicon is passivated and modified properly—for example, with delta-doping—the silicon imagers can achieve the highest performance possible in sensitivity and spectral range. The band-structure modification via delta-doping technology developed at MDL has resulted in 100% internal quantum efficiency, low surface-generated dark current, and exceptional uniformity and stability small-format silicon imagers. JPL has embarked on an effort to expand this unique capability with high-throughput and high-yield production in response to the detector needs of the future survey missions.

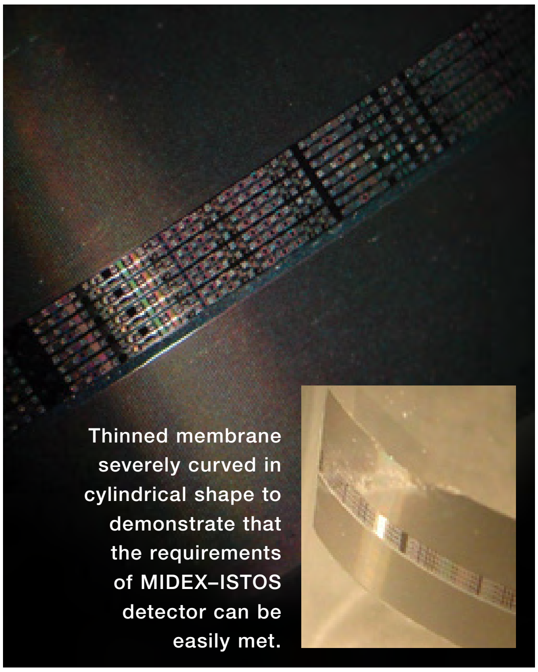
DETECTOR DEVELOPMENT FOR MEDIUM EXPLORER–IMAGING SPECTROSCOPIC TELESCOPE FOR ORIGINS SURVEYS (MIDEX–ISTOS)

Using JPL Discretionary R&D Funds (DRDF), we are developing a detector for a future mission, MIDEX–ISTOS. MIDEX-ISTOS is a mission concept (PI, Chris Martin, Caltech) to study the intergalactic medium and cosmic web of matter. It requires UV detectors that surpass the performance of any detectors ever flown. In order to surpass the science goals that were achieved by Hubble Space Telescope and Galaxy Evolution Explorer, ISTOS detectors must have capabilities that move beyond traditional microchannel plate technology and toward modern, solid-state-based photon counters that are enhanced with JPL UV sensitization technology (delta-doping). In addition, the wide field of view design of ISTOS requires a curved focal plane array. Delta-doping and another MDL innovation, curved imagers, applied to CCDs with avalanche gain enable ISTOS to meet its science requirements.

OTHER CURRENT PROJECTS AND TECHNOLOGIES UNDER DEVELOPMENT

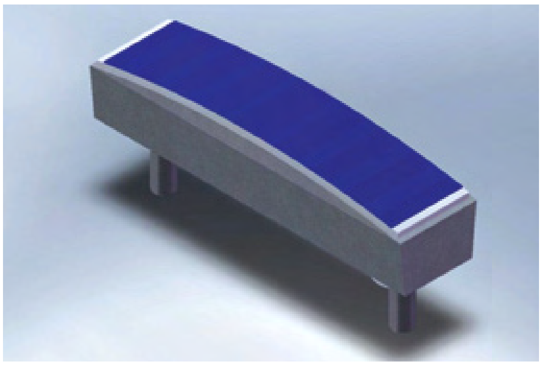
- Curved focal plane arrays
- Solid-state solar-blind UV detector arrays: GaN focal plane arrays
- Photon-counting UV detector arrays: GaN avalanche photodiode arrays
- Photoemissive solar-blind UV detector arrays: electron bombarded arrays and III-N photocathodes
- Hyperspectral imaging
- Simultaneous spectral-temporal adaptive Raman spectrometers (SSTARS)

2008 Highlights: A new silicon MBE with the capacity to process up to 8-inch wafers in batches of multiple wafers was co-designed with Veeco and procured from Veeco through JPL's equipment funds. With JPL's investment in this new capability, it will be possible to respond to the demands of producing a large number of large-area arrays in order to

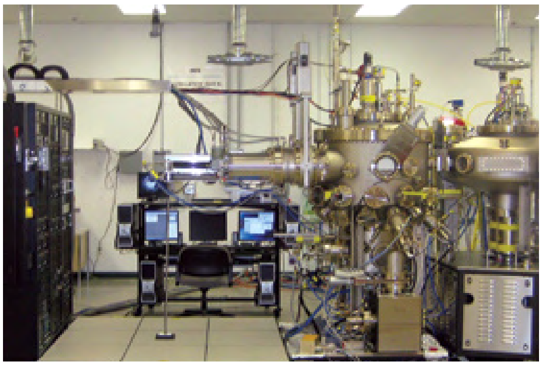


Thinned membrane severely curved in cylindrical shape to demonstrate that the requirements of MIDEX–ISTOS detector can be easily met.

SILICON IMAGERS CONTINUE TO BE THE BEST DETECTORS FOR THE ULTRAVIOLET–NEAR-INFRARED (UV-NIR) SPECTRAL RANGE.



Concept of curved detector array for MIDEX-ISTOS. The required curvature of 200 mm is modest and has been demonstrated by the MDL group.



Photograph of the JPL 8-inch Gen200 MBE manufactured by Veeco.

respond to the requirement of future large FPAs. The new silicon MBE will be received and installed at JPL in 2009.

The first Joint Dark Energy Mission–SuperNova Acceleration Probe (JDEM–SNAP) format delta-doped CCD was demonstrated. This 10-megapixel, 3.5k×3.5k device was not only delta-doped at JPL, all post-fabrication processes related to back illumination were performed at JPL, including thinning by chemical-mechanical polishing, packaging, and testing.

We initiated a collaboration with the Rochester Institute of Technology and University of Rochester to develop back-illuminated delta-doped CMOS imagers that are radiation tolerant and low noise.

Another emerging collaboration is with UC Berkeley/Lawrence Berkeley National Laboratory for delta-doped CMOS-SOI particle detectors.

The Caltech/JPL delta-doped and AR-coated p-channel CCDs were selected for the ground-based Wide Field Multi Object Spectrometer (WFMOS) instrument for the Subaru telescope. WFMOS is a very ambitious project: a spectrometer capable of targeting several thousand objects simultaneously by individually positioning optical fibers across a 1.5 square degree field of view. The major science goal is to study the mysterious dark energy in the universe using three-dimensional maps of the matter distribution obtained by pinpointing the 3D locations of millions of galaxies.

The MIDEX–ISTOS concept is under formulation, and curved delta-doped photon-counting FPAs have been baselined for the mission. The telescope design for ISTOS demands a cylindrically curved array; a cylindrically curved CCD that surpasses the ISTOS curvature requirements was rapidly demonstrated at MDL. This work built on techniques for spherically curved arrays previously demonstrated at MDL.

In addition to the MIDEX-ISTOS, delta-doped CCDs for broadband imaging or delta-doped p-channel photon-counting detectors were baselined for several other MIDEX concepts and mission concepts funded in the study phase for decadal survey study. These included MIDEX–Orbiting Medium Explorer for Gravity Astrophysics (OMEGA), NASA Astrophysics Strategic Mission Concept Studies (ASMCS)–Star Formation Observatory, and ASMCS-Theia.

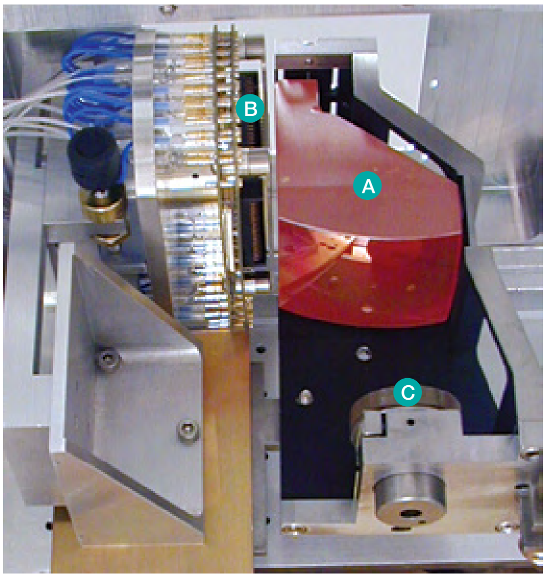
Picture of the first 640x512 pixel portable long-wavelength infrared QWIP camera. Lightweight and low cost portable infrared cameras like this makes it attractive to many new applications never thought of.

INFRARED PHOTONICS

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.

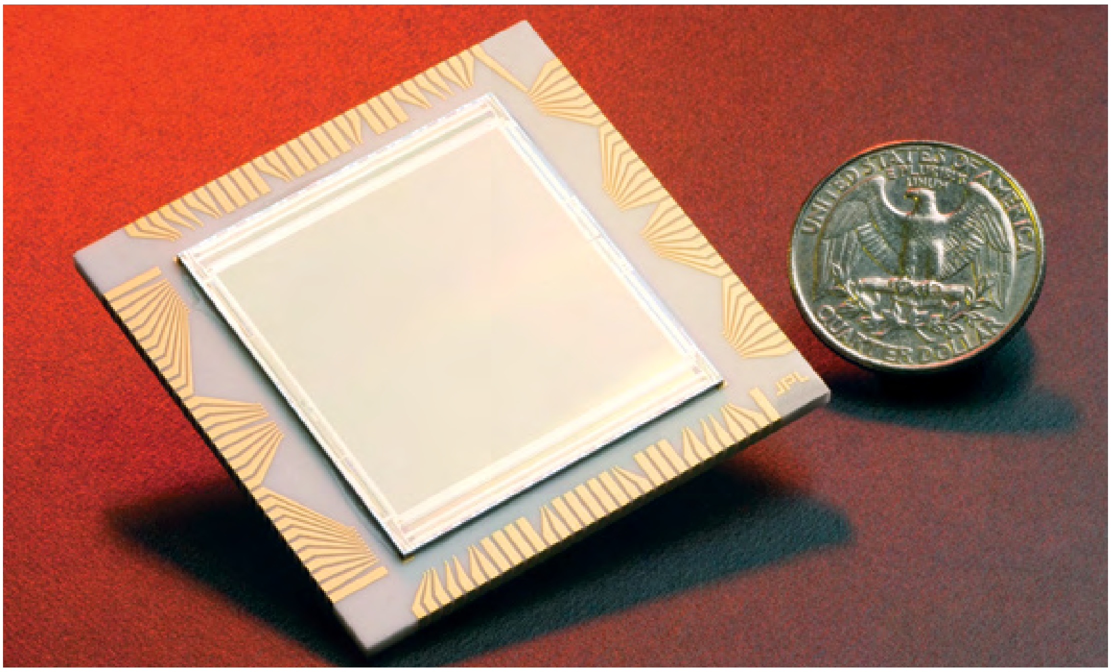
Intrinsic infrared detectors in the long-wavelength range (8–20 μm) are based on interband transitions, in which a photon promotes an electron across the bandgap from the valence band to the conduction band. These photoelectrons can be collected efficiently, thereby producing a photocurrent in the external circuit. The bandgap sets the minimum energy that a photon must have in order to be absorbed and detected. Therefore, the spectral response of the detector can be controlled if the photosensitive material has an adjustable bandgap. Such materials can be found in the II-VI group alloys, in which the energy gap can be controlled by varying the molar ratio of materials. That means detection of very-long-wavelength infrared radiation up to 20 μm requires small bandgaps down to 62 meV. It is well known that these low-bandgap II-VI materials are more difficult to grow and process than large-bandgap III-V alloy semiconductors such as GaAs. These difficulties motivate the exploration of utilizing the intersubband transitions in multiquantum-well (MQW) structures made of large-bandgap semiconductors and interband transitions in III-V superlattices.

Currently, the infrared photonics technology group is working on strained layer superlattices, barrier infrared detectors (BIRD), quantum-well infrared photodetectors, and quantum-dot-based infrared photodetectors for space and terrestrial applications. Novel high-performance quantum-well and quantum-dot–based solar cells are being developed, as well as InGaN-based solar cells for eventual space applications.



Photograph of the QWEST Dyson Spectrometer showing A) the ZnSe Dyson Block, B) an 8–12-mm multiband QWIP focal plane, and C) a concave diffraction grating.

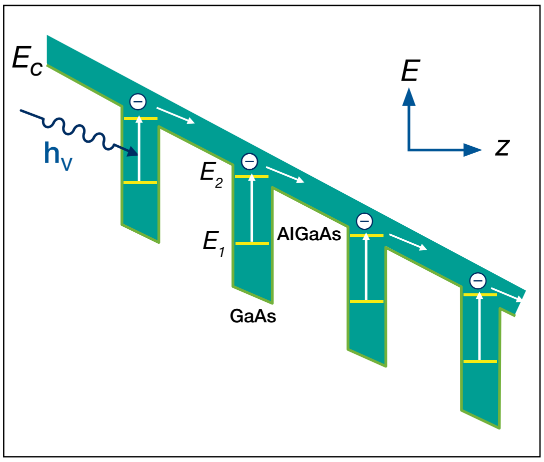
CURRENT PROJECTS



Photograph of a 1024×1024-pixel dual-band QWIP FPA mounted on a 124-pin lead-less chip carrier fabricated at MDL.

DUAL-BAND MEGAPIXEL QWIP FOCAL PLANE ARRAY

A dual-band FPA camera would provide the absolute temperature of a target with unknown emissivity, which is extremely important to the process of identifying a temperature difference between missile targets, warheads, and decoys. Dual-band infrared FPAs can also play important roles in Earth and planetary remote sensing, astronomy, and other applications. Furthermore, monolithically integrated pixel-co-located, simultaneously readable, dual-band FPAs eliminate the beam splitters, filters, moving filter wheels, and rigorous optical alignment requirements imposed on dual-band systems based on two separate single-band FPAs or a broad-band FPA system with filters. Dual-band FPAs also reduce the mass, volume, and power requirements of dual-band systems. Due to the inherent properties such as narrow-band response, wavelength tailorability,



Schematic diagram of the conduction band in a bound-to-quasibound QWIP.

THE PHOTOSENSITIVE MQW REGION OF EACH QWIP DEVICE IS TRANSPARENT AT OTHER WAVELENGTHS, WHICH IS AN IMPORTANT ADVANTAGE OVER CONVENTIONAL INTERBAND DETECTORS.

and stability (i.e., low 1/f noise) associated with the GaAs-based QWIP, it is an ideal candidate for large-format dual-band infrared FPAs.

2008 Highlights: Demonstrated the first megapixel, dual-band, pixel-co-located, simultaneously readable QWIP FPA. This dual-band QWIP device is based on 4–5-μm mid-wavelength infrared (MWIR) and 7.5–9-μm long-wavelength infrared (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 MBE. 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 given the difficulty of the fabrication process. Video images were taken at a frame rate of 30 Hz at temperatures as high as 70K, 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 μm and dimensions of the FPA are 34×39 mm^2. The initial GaAs substrate of these dual-band FPAs is completely removed, leaving only a 50-nm–thick GaAs membrane. Thus, these dualband QWIP FPAs are not vulnerable to delamination and

An image taken with the first megapixel simultaneously readable, pixel-co-registered MWIR:LWIR dual-band QWIP camera. The flame in the MWIR image *(left)* looks broader due to the detection of heated CO_2 *(from cigarette lighter)* re-emission in 4.1–4.3-μm band, whereas the heated CO_2 gas does not have any emission line in the LWIR (8–9 μm) band. Thus, the LWIR image shows only thermal signatures of the flame.

indium bump breakage during thermal recycling process, and they have negligible pixel-to-pixel optical cross-talk.

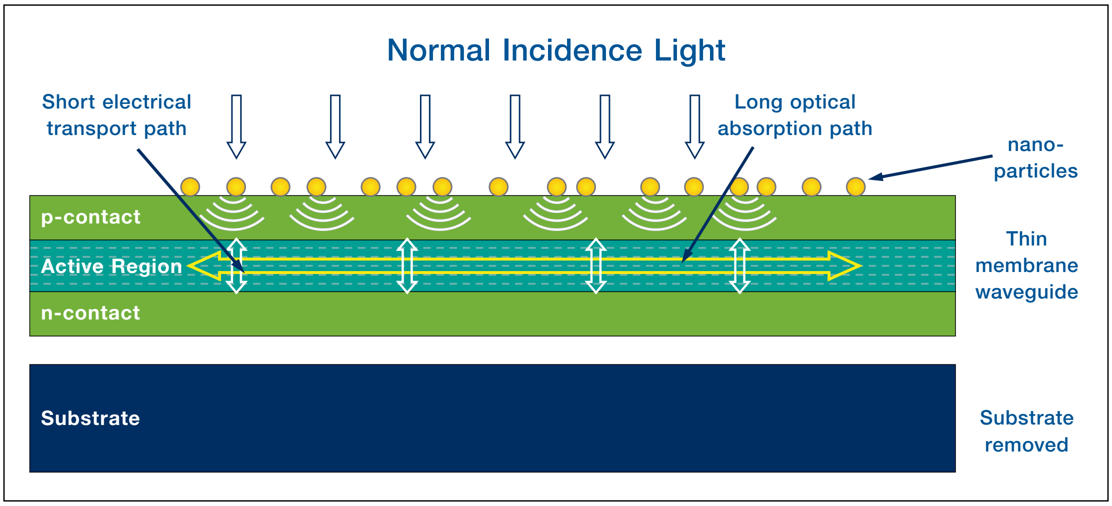
SUPERLATTICE-BASED AND ANTIMONIDE BIRD FOCAL PLANE ARRAYS

Superlattice photodiodes made from type-II InAs/GaSb quantum wells are the next step in LWIR FPAs. Like QWIPs, they are made from III-V materials, but have enhanced quantum efficiency. Due to their high quantum efficiency, superlattices are the leading candidate for displacing HdCdTe as the technology of choice for low-background applications.

The BIRD detector is an important addition to the MWIR applications. This detector uses a bulk or superlattice absorbing layer and a monolithically integrated dark current blocking layer. This layer also serves as a passivation layer, allowing for planar processing in array fabrication. A typical BIRD uses InAs or InAsSb as the absorbing layer and an alloy of AlSb of the blocking layer. These detectors are inherently high performance, and diffusion limited at low temperatures as well as high. BIRD arrays are rapidly becoming competitive with InSb as the technology of choice for MWIR applications.


Image taken with new 640x512 BIRD MWIR camera.

SUPERLATTICE PHOTODIODES MADE FROM TYPE-II INAS/GASB QUANTUM WELLS ARE THE NEXT STEP IN LONG-WAVELENGTH INFRARED FOCAL PLANE ARRAYS.



Solar structure with short active region for carrier extraction from quantum wells/dots and thinned and coated with nano-particles for scattering light into guided modes.

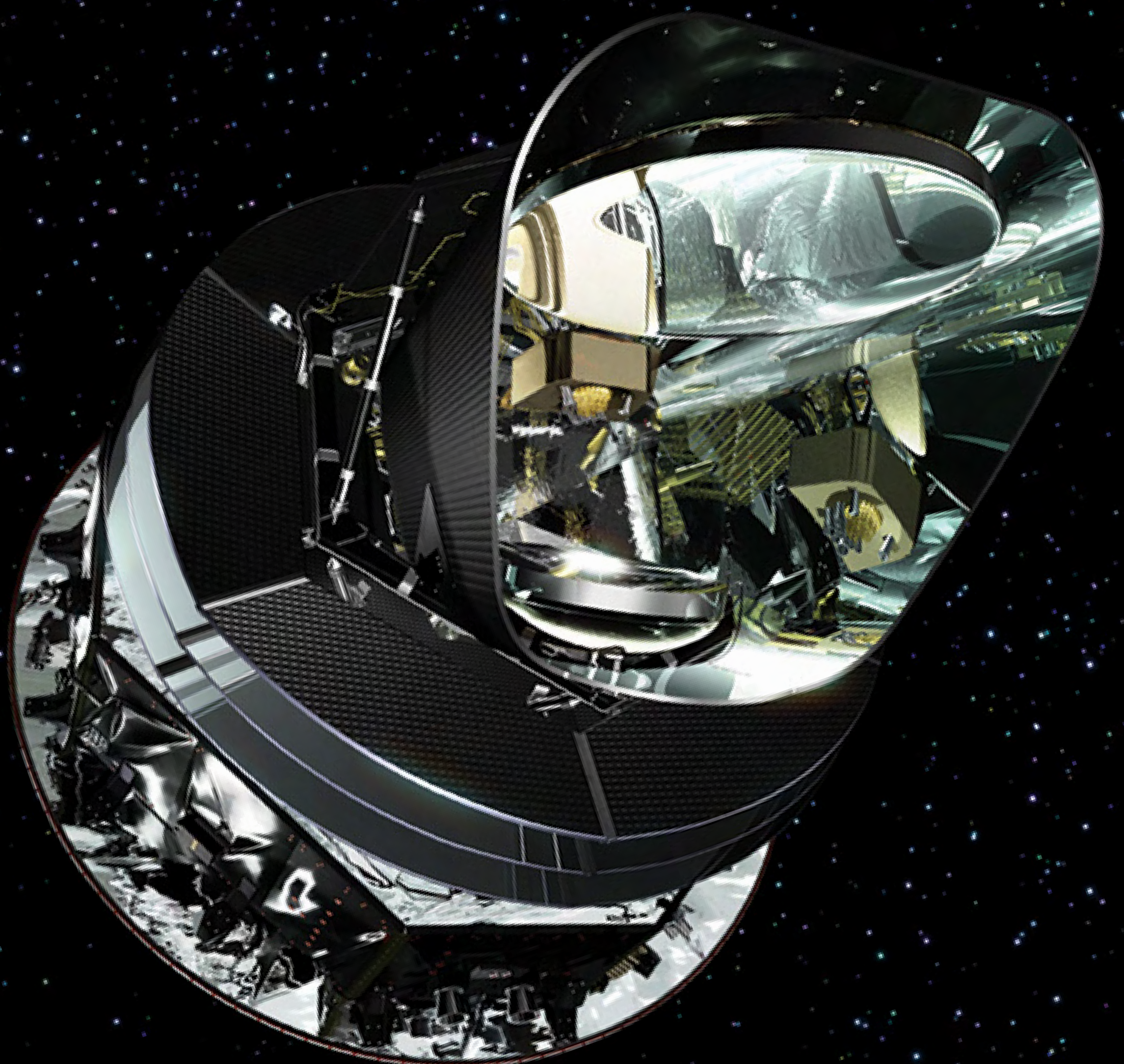
2008 Highlights: Developmental arrays based on superlattices in the LWIR and BIRD material in the MWIR have also been demonstrated. For the first time, high QE LWIR superlattice detectors with a 77K RoA value of over 1000 Ohm cm^2 have been demonstrated and fabricated into 256x256 arrays. 640x512 MWIR BIRD arrays have been fabricated showing high QE and excellent imaging quality up to 220K with a long wavelength cutoff of 4.2 µm. Additionally, we have demonstrated a megapixel MWIR imaging array based on superlattice diodes.

ULTRATHIN QUANTUM STRUCTURE SOLAR CELLS

In collaboration with Professor Ed Yu Group (University of California, San Diego), JPL is developing an advanced ultra-thin single-junction solar cell as an alternative to multi-junction tandem cells. These solar cells are based on the integration of semiconductor photovoltaic quantum structures (quantum wells and quantum dots) with nanoscale metallic or dielectric particles engineered to produce scattering of incident photons into laterally propagating, optically confined modes within the quantum well/dot regions, enabling very high efficiency in photon absorption and photocurrent generation within ultrathin layers. This approach increases the wavelength range of the solar spectrum that can be absorbed, increases the effective path length of light for absorption through the cell, and improves the collection of photogenerated carriers from the increased electric field within the quantum well/dot region.

2008 Highlights: Demonstrated extended response in solar cells with embedded quantum wells and quantum dots. These ultrathin (~0.3 mm absorber thickness) solar cells have excellent fill factor (>0.8) and efficiency (>10.7%, without anti-reflection coating), measured under 1 sun, air mass zero (AM0) conditions These solar cells serve as the basis for very-high-performance solar cells: Electromagnetic simulations indicate that a factor of 2–3 increase in performance is obtainable when these cells are thinned into waveguide structures and enhanced with nano-particles.

MDL's spider web bolometers will be launched in 2009 on the HFI instrument for the European Space Agency's (ESA) Planck mission. Their focus is to study anisotropies in the cosmic microwave background radiation.



Artwork courtesy of ESA. Image by AOES Medialab.

SUPERCONDUCTING MATERIALS AND DEVICES

THE JPL SUPERCONDUCTING MATERIALS AND DEVICES GROUP'S PRIMARY FOCUS IS ON CRYOGENIC MILLIMETER & 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 will be 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 and superconducting single-photon detectors for optical communications.

More recent development efforts have focused on large-format arrays of direct detectors for spectroscopy, imaging, and polarimetry. This effort began with the development of spider web bolometers, which will be launched in 2009 on the HFI 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 are currently being delivered for the BICEP II instrument at the South Pole and for the SPIDER balloon-borne telescope. In addition to producing valuable science, these projects are important technology demonstrations for future space missions to study the inflation that occurred in the earliest stages of the Big Bang.

Microwave kinetic inductance detectors (MKIDs) were 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 camera on the Caltech Submillimeter Observatory, and are also being developed for a camera for the 200" telescope on Mount Palomar.

CURRENT PROJECTS

SIS MIXERS

SIS mixers are currently being delivered for the Smithsonian Astrophysical Observatory's Submillimeter Array in Hawaii, 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.

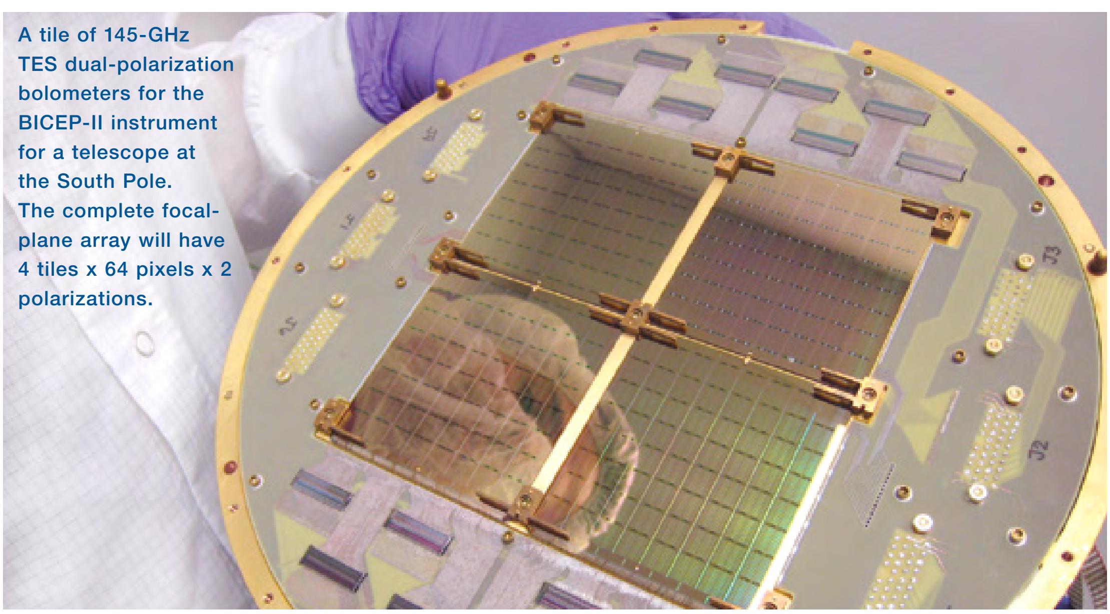
TES BOLOMETERS

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

2008 Highlights: TES arrays for polarimetry are being delivered for the BICEP-II ground-based telescope at the South Pole, and for the SPIDER balloon-based suborbital telescope. 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 CMB-Pol.

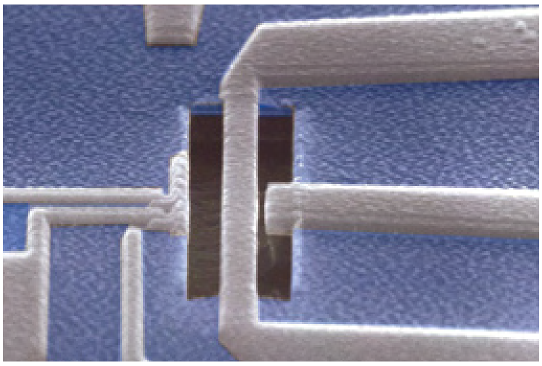
MKIDs

MDL is focused on two major MKID development projects: the development of energy-resolving, photon-counting optical detector arrays, and the development of multiband submillimeter-wave imaging arrays. The

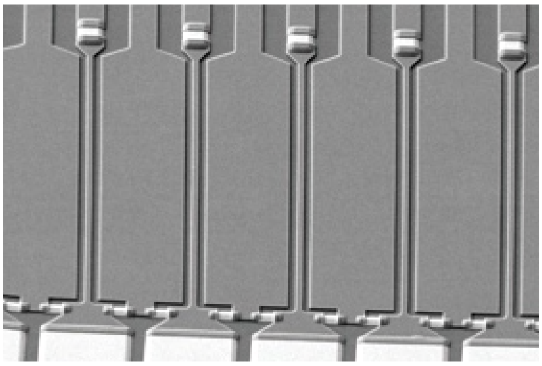


A tile of 145-GHz TES dual-polarization bolometers for the BICEP-II instrument for a telescope at the South Pole. The complete focal-plane array will have 4 tiles x 64 pixels x 2 polarizations.

IN 2008, SNSPDs WERE BASELINED FOR A GROUND-BASED RECEIVER FOR THE LUNAR ATMOSPHERE AND DUST ENVIRONMENT EXPLORER MISSION (LADEE).



SEM image of a nanoresonator coupled to a single-Cooper-pair box device.



An array of Ta/Al MKID strip detectors is being fabricated for a 64 x 20–pixel camera camera.

optical detectors will be used in a camera for the 200" Mount Palomar telescope, while the submillimeter detectors will be used in a large camera being constructed for the Caltech Submillimeter Observatory. These ground-based large-system demonstrations serve as essential precursors to the potential use of MKIDs in space astrophysics missions such as CMBpol, SAFIR, Constellation-X, and TPF-C.

2008 Highlights: The origin of the excess noise seen in MKIDs was traced to a thin (several nm) layer of amorphous dielectric material residing on the surface of the device, possibly a thin native oxide layer or a layer of adsorbed water ice. This breakthrough, described in a series of papers in Applied Physics Letters, provides the solution to a five-year-old puzzle and suggests several new routes toward achieving extremely high sensitivity. Initial steps along these lines have already resulted in a substantial reduction in noise, providing strong confirmation of the diagnosis and illustrating the future opportunities.

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.

2008 Highlights: In 2007, MDL/JPL-developed SNSPDs were demonstrated to have the best performance reported to date. In 2008, SNSPDs were baselined for a ground-based receiver for the LADEE (Lunar Atmosphere and Dust Environment Explorer) mission.

QUANTUM COMPUTATION

Superconducting circuits are one possible approach to realization of quantum computation, which can potentially solve problems that are not addressable even with supercomputers. Charge qubits using superconducting single-Cooper-pair boxes is one approach under investigation, and an alternate adiabatic approach is also being investigated in collaboration with a small company, D-Wave Systems Inc.

2008 Highlights: Manipulation of one qubit and quantum entanglement of two qubits has been demonstrated with superconducting charge qubits based on single-Cooper-pair boxes.

The Herschel Space Observatory includes the Heterodyne Instrument for the Far Infrared (HIFI). All of the submillimeter-wave devices used for the local oscillators on HIFI were designed and fabricated at the MDL.

Artwork courtesy of ESA. Image by AOES Medialab.

SUBMILLIMETER DEVICES

THE SUBMILLIMETER-WAVE ADVANCED TECHNOLOGY (SWAT) GROUP SPECIALIZES IN DEVELOPING AND IMPLEMENTING SUBMILLIMETER-WAVE AND TERAHERTZ REMOTE-SENSING TECHNOLOGIES FOR A VARIETY OF APPLICATIONS FROM NASA MISSIONS TO NOVEL NON-SPACE APPLICATIONS.

For many years, JPL has been at the forefront in development of components and technologies to enable spaceborne instruments based on high-resolution heterodyne spectrometers for Earth remote-sensing missions, planetary missions, and astrophysics observatories. The wide-ranging technical expertise in this area 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 are key elements in accomplishing the strategic goals of the Jet Propulsion Laboratory. Technologies developed have enabled the following science in recent years:

- Spectroscopic measurements 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 will help explain the origins and behavior of planets, stars, and galaxies.
- Through future high-resolution interferometric observations, these new instruments may be able to detect and quantify the chemical constituents of life on extra-solar system planets.
- Using in situ measurements, these new 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 is 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.

The Herschel Space Observatory during final stages of testing before being shipped for launch.

CURRENT PROJECTS

COMPACT SUBMILLIMETER-WAVE SOURCES

Work during FY08 included demonstrating a JPL-developed two-chip power-combined tripler working across the 260–340-GHz band. A Y-junction power splitter and power combiner are utilized to increase the power-handling capability of this circuit. The two chips mounted in the block, along with the block, are shown below. The circuit can now handle 3 dB more input power that translates to 3 dB more output power. Such a circuit has shown to produce more than 20 mW at the design frequency. This particular circuit was then used to pump a 900-GHz tripler. This x3x3 combination produced a world record 1.2 mW at 930 GHz when cooled to 77 K.

2008 Highlights: Demonstrated 1 mW of output power at 930 GHz (a new world record). Work is under progress to build a solid-state local oscillator chain to 2700 GHz.

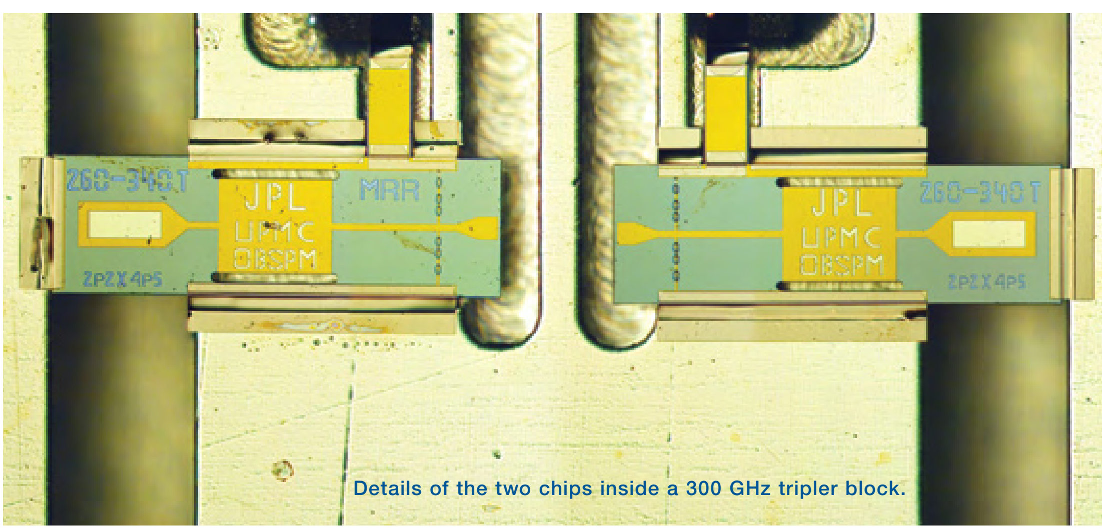
SCHOTTKY DIODE MIXERS

GaAs planar Schottky diode mixers based on a membrane diode process have been used to make a number of different mixer topologies in the 400–600-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. Subharmonic mixers covering the 530–590-GHz range have demonstrated sensitivities better than 5000 K DSB across the band. These mixers are designed with bias capability allowing the mixers to be operated with reduced LO power requirements. These planar Schottky mixers are baselined for missions to Venus and Mars.

2008 Highlights: Developed and demonstrated Schottky diode subharmonic mixers in the 440–874-GHz range.

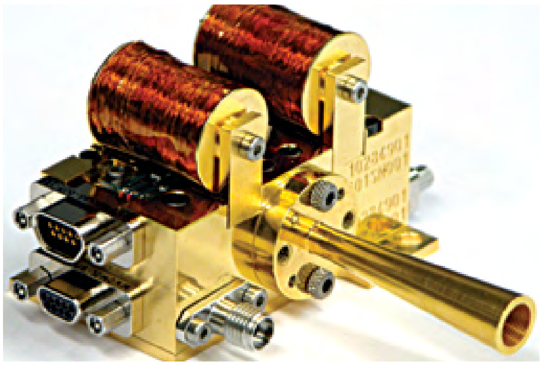
SIS RECEIVERS FOR STUDYING GLOBAL ATMOSPHERIC CHEMISTRY

MDL is developing a 180–280-GHz sideband-separating superconductor-insulator-superconductor (SIS) receiver for the Scanning Microwave Limb Sounder (SMLS) instrument of the future Global Atmospheric Chemistry Mission (GACM). The niobium aluminum-nitride devices for the sideband separating receiver were fabricated in the MDL to a

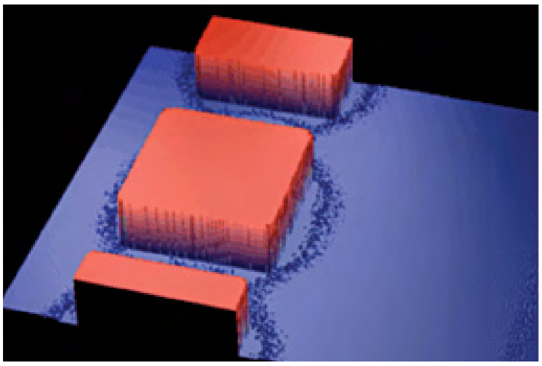


Details of the two chips inside a 300 GHz tripler block.

THE JPL-DEVELOPED MONOLITHIC MEMBRANE DEVICE (MoMeD) PROCESS ALLOWS ONE TO INCORPORATE A NUMBER OF DESIGN FEATURES AT THE CHIP LEVEL THAT ALLOW FOR INCREASED FUNCTIONALITY WITHOUT SACRIFICING PERFORMANCE.



A compact sideband-separating SIS mixer block covering 180–280 GHz with state-of-the-art performance has been demonstrated.



Part of the 325-GHz quadrature hybrid showing surface roughness measurement done by the Wyko Interferometer System. The etching was done in a deep RIE system in the MDL.

Caltech design. The mixer demonstrated world-class performance when measured in a sideband-separating receiver.

2008 Highlights: Demonstrated SIS sideband-separating mixers in the 180–280-GHz band and single-ended mixers in the 580–680-GHz band for the Scanning Microwave Limb Sounder (SMLS) instrument of the GACM called for in the Earth Science Decadal Survey.

FABRICATION OF SUBMILLIMETER-WAVE COMPONENTS VIA DRIE TECHNOLOGY

JPL is using deep reactive ion etching (DRIE)-based silicon micromachining capabilities to develop the critical waveguide components at submillimeter wavelengths that will lead to highly integrated multi-pixel spectrometers, imagers, and radars. A silicon-based quadrature hybrid working in the 325–500-GHz range has been designed and initial fabrication is in progress.

2008 Highlights: Silicon micromachining was utilized to fabricate a quadrature hybrid at 325 GHz.

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.

The key submillimeter components of the system are fabricated in the MDL. They consist of two chains of GaAs-based Schottky-diode doublers and triplers and a fundamental balanced mixer. These all-solid-state components ensure high transmit powers (~1 mW) and low-noise detection (TE~4000 K DSB) at 570–600 GHz. Worldwide, the MDL is the only source of these high-performance devices, and they are crucial to the successful operation of the terahertz imager.

2008 Highlights: The first demonstration of an active imaging radar at 600 GHz with resolution better than 1 cm from a distance of 4 meters (funded by the U.S. Navy).

Does life exist on Mars? MDL is collaborating with UC Berkeley to develop the Microcapillary Electrophoresis instrument for the 2016 ExoMars mission.

It has the critical job of separating different types of organic compounds from one another for identification, including the separation of mirror-image amino acids.

Artistic representation of the ExoMars Rover.

IN SITU SENSORS FOR LIFE DETECTION

MDL HAS PARTNERED WITH THE UNIVERSITY OF CALIFORNIA AT BERKELEY AND NASA/AMES TO DEVELOP LAB-ON-A-CHIP SYSTEMS TO INVESTIGATE THE PRESENCE OF ORGANIC COMPOUNDS IN THE MARTIAN REGOLITH, AS WELL AS SENSORS TO ASSESS THE OXIDATION EFFECTS THAT THE MARS ENVIRONMENT WOULD HAVE UPON POSSIBLE ORGANIC MATERIAL OR BIOCONTENT.

Microfabricated chemical and biochemical sensors and systems offer some of the most promising approaches to astrobiological small-payload investigations in space exploration. These systems can provide unique functionality with high sensitivity and limited power, mass, and volume requirements, making them a logical choice for small payload implementation. An example is the Urey instrument under development at JPL for the Mars 2016 ExoMars mission. Urey will perform astrobiological investigations on the Martian surface and has the potential of performing the first successful detection of bioorganic compounds on Mars. The Urey instrument consists of three subsystems, two of which are heavily dependent on microfabrication technologies: the Mars Oxidant Instrument (MOI) and the Microcapillary Electrophoresis (μCE) instrument.

THE MARS OXIDANT INSTRUMENT (MOI)

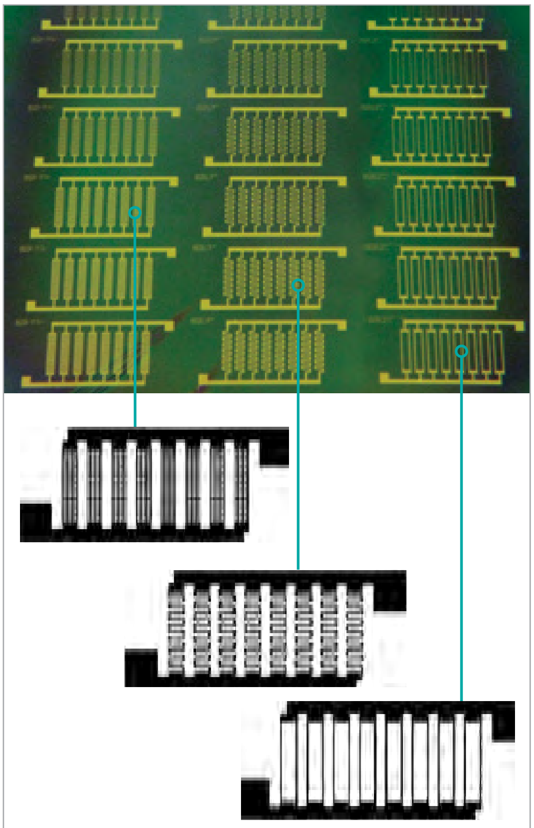
The MOI, an array of chemiresistive sensors, determines the reactivity of organic molecules within the host regolith based on the chemical reactivity of surface and atmospheric oxidants. Atmospheric and soil oxidants present in the Martian environment can be detected by measuring the change in the resistance of thin solid-state films after exposure to Martian samples. These solid-state films are deposited by evaporation or solvent casting over a set of metal electrodes. The resulting resistance of these films is an extremely sensitive function of the ambient environment (gases or regolith). Furthermore, because of the extreme precision and accuracy by which the current and voltage can be determined, the chemiresistor is one of the best transducer configurations for high-sensitivity applications.

THE MICROCAPILLARY ELECTROPHORESIS (μCE) INSTRUMENT

The μCE, which is based on a microfluidic system, uses dry or wet samples extracted from the Martian regolith and performs automated sample handling, dilution, mixing, fluorescent labeling, and electrophoresis. Detection is performed via laser-induced fluorescence near the output of the electrophoresis microchannel as a function of time after sample introduction. By measuring and calibrating the ratios of amino acid chirality (handedness) in samples analyzed, the system is able to ascertain whether detected species were produced by biotic or abiotic processes.

These technologies under development are ideal candidates for potential in situ instruments for other future missions to targets such as Titan, Europa, or Mars.

CURRENT PROJECTS



SiNx membrane with a variety of electrode configurations on a 4-inch wafer.

MOI

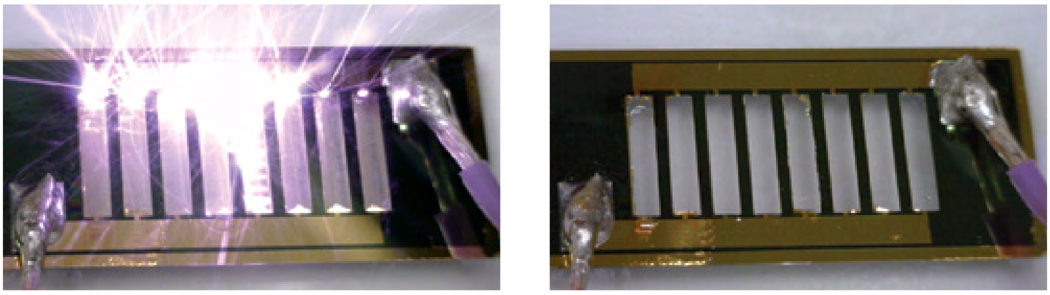
The MOI requires the development of hermetically sealed packages to protect the films during storage and transit. The technology for achieving these hermetic seals, and their controlled rupture on Mars (to enable exposure of the films to samples when desired) is being developed at JPL. This technology involves the use of thin silicon nitride membranes, with electrical "microheater" elements that enable electrically triggered rupturing of the seals.

2008 Highlights: The feasibility of vaporizing the SiNx membranes by electrically triggering the films via electrodes on top of the thin membrane has been studied. Two distinct approaches for bursting the membranes have been developed and are currently being evaluated:

1. Spiking a large charge through a metal lead that has a low melting point, causing the metal to melt and explode in the form of metal vapor plasma causing the burst of the membrane.

2. Running electrical current through a high-melting-point metal to thermally induce and stress-fracture the membrane.

Both of the techniques have shown the ability to blow open nitride membranes.



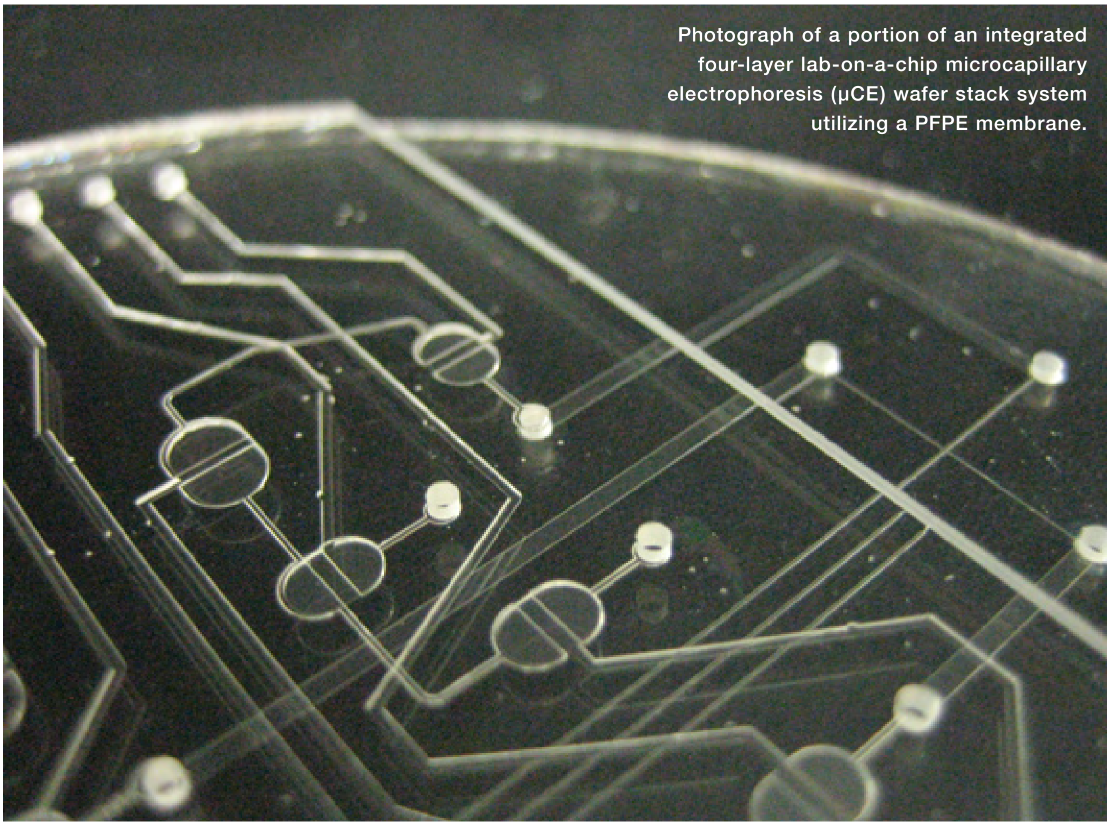
Demonstration of sensor deployment using electrical rupturing of the SiNx membrane in 10 torr CO_2 (Mars ambient). Left: DC voltage is applied to the electrodes. Right: Membrane is removed and the sensor is exposed.

IN COLLABORATION WITH LIQUIDIA CORPORATION, FLUOROCUR PERFLUOROPOLYETHER (PFPE) MEMBRANE DEVICES WERE DEVELOPED AS A NEW MATERIAL SYSTEM.

MICROCAPILLARY ELECTROPHORESIS (µCE) CHIP

The µCE system under development consists of (1) a multilayer wafer stack that performs fluidic manipulations and electrophoresis analysis, (2) a manifold system that brings in the sample and chemicals for reaction, and (3) a laser fluorescence detection system that records fluorescence from the desired microchannel.

2008 Highlights: Development of reliable microfluidic components. The challenge during the past year was to develop and qualify a robust material system and fabrication technique of valves and pumping systems that could survive the wide range of environmental conditions associated with the spaceflight environment. In collaboration with Liquidia Corporation, fluorocur perfluoropolyether (PFPE) membrane devices were developed as a new material system. A comprehensive stress-testing protocol was adopted in order to compare the reliability of Teflon, PFPE, and commonly used polydimethylsiloxane (PDMS) membranes and pumps. The fabricated devices were subjected to hundreds of thousands of actuations and 30 temperature cycles where devices were alternately cooled to -50°C and heated to +50°C. Our experimental results confirmed that the new material system, fluorocur, was the most robust option for the lab-on-a-chip for the space environment, and is currently under continued development for application in the Urey Instrument, as part of the ESA ExoMars mission.



Photograph of a portion of an integrated four-layer lab-on-a-chip microcapillary electrophoresis (µCE) wafer stack system utilizing a PFPE membrane.

Single bundles of multiwalled carbon nanotube field emitters monolithically integrated with electron beam tailoring electrodes using silicon micromachining.

NANO AND MICRO SYSTEMS

THE NANO AND MICRO SYSTEMS (NAMS) EFFORT AT MDL FOCUSES ON APPLICATION-DRIVEN NANO AND MICRO DEVICES AND TECHNIQUES FOR IN SITU AND REMOTE PLANETARY EXPLORATION. TECHNOLOGY DEVELOPMENT COVERS THE AREAS OF ELECTRON BEAM-BASED MICROSYSTEMS, MICROELECTROMECHANICAL SYSTEMS, AND NANOSENSORS/ELECTRONICS.

Miniaturization of components and instruments enhances the payload capability. Efficient electron sources are the fundamental components of: (1) miniature vacuum tube sources for high-frequency applications, (2) multiple analytical instruments to perform elemental and mineralogical analyses, and (3) vacuum microelectronic devices to develop radiation-insensitive, extreme-environment-withstanding electronics. Each application requires a specifically designed electron source in terms of beam-forming optics and the emission density that spans a range of tens to hundreds of amperes per square cm. The state-of-the art thermionic cathodes are ill-suited for miniature instruments because of their bulkiness, high temperature operation, and high power consumption. The state-of-the-art cold cathodes that are based on atomically sharp micromachined tips are highly susceptible to poisoning when operated in non-UHV (10^{-8} to 10^{-9} Torr) environments. Such vacuum levels are not possible in micromachined vacuum cavities necessary for miniaturization. Interest in high-current-density electron sources that are robust to poor vacuums and are capable of operation at low voltages is motivated by the re-emerging vacuum tube technology for high-frequency sources. Research is ongoing to realize portable, narrow-band, coherent CW sources of tunable RF power in the submillimeter-wave frequency bands (300–3000 GHz) for active (and passive) sensor systems based on vacuum tube technology. It has been shown that for such devices the current density requirement is in the range of tens to hundreds of amperes per cm^2.

JPL-developed carbon nanotube (CNT) bundle array technology for field emission has been one of the few known cold cathode technologies able to address the high-current density needs mentioned above while operating in poor vacuums achievable in micromachined cavities (10^{-6}–10^{-5} Torr). We are currently applying this technology for 220-GHz tube sources. Recently we have also demonstrated programmable logic gate concept using these bundles in vacuum microelectronics configuration at temperatures as high as 700° C. We have shown low-power, high-efficiency X-ray tubes for next-generation mineralogy instruments such as XRD/XRF spectroscopes. Many more new devices are being conceived and implemented to address needs in high-temperature power sources, thermal coupling materials, multifunctional materials for microrobotics, base structures for hydrogen production for fuel cells, and for immunotherapy of brain tumors (with City of Hope Cancer Research Center).

Additionally, devices such as microgyroscopes, Atmospheric Electron X-ray Spectrometer, extreme environment microsensors have been developed at MDL.

CURRENT PROJECTS

VACUUM PACKAGING AND VACUUM GAUGING IN MICROCAVITIES

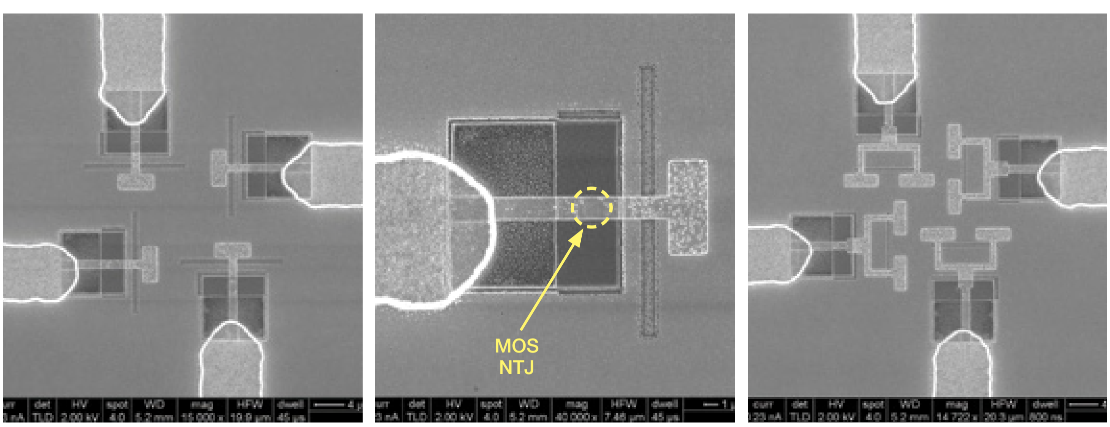
Miniaturization is often associated with creating high-vacuum microcavities. Two problems faced while making vacuum microcavities are the level of vacuum that can be attained and preserved for prolonged periods, and monitoring this vacuum once the package is sealed. Ongoing projects such as disc resonating microgyroscope (DRG), vacuum microelectronics, miniature spectrometers, and high-frequency sources can all use reliable vacuum packaging and vacuum monitoring technologies.

2008 Highlights: A vacuum packaging technique that uses solder-reflow of Sn/Au alloy was developed to enclose disc resonators for microgyroscope application. Using carbon nanotubes as field emitters, we were able to characterize the vacuum inside the package after a shelf life of 6 months. Along with that, a stand-alone bridge structure of single-walled nanotube was developed to measure pressure as a function of conductivity. These gauges functioned reliably as broad-dynamic range sensors with sensitivity from atmospheric pressure down to high vacuums of 10^{-6} Torr.

NAVIGATIONAL GRADE INTEGRATED MICROGYROSCOPES (NGMIG)

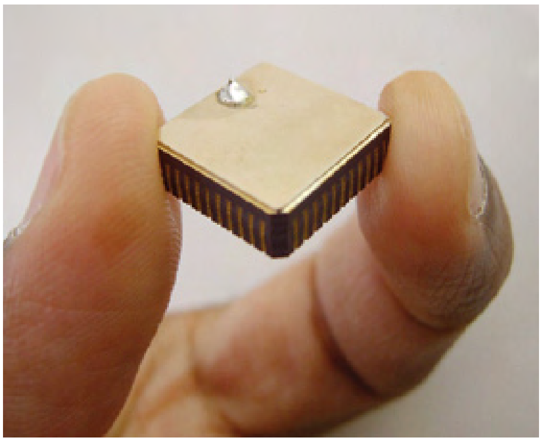
The objective of the JPL MEMS gyroscope project is to build a high-accuracy, inexpensive, compact, lightweight, low-power gyroscope. Currently, high-performance inertial technology is dominated by inertial measurement units (IMUs) employing ring laser gyroscopes (RLGs) or fiber optic gyroscopes (FOGs). All IMUs based on optical gyros are relatively large and power consumptive. In addition, optical gyros suffer from dead-band nonlinearities and light source life issues. Microelectromechanical systems (MEMS)–based gyros offer the advantages of small volume and mass, low power, and reduced cost through batch fabrication; however, MEMS gyros have traditionally suffered from lower performance. The JPL MEMS gyroscope effort has been aimed at achieving comparable performance to optical gyroscopes while retaining all the advantages of MEMS devices. Achieving this goal would allow utilization on every single NASA mission.

2008 Highlights: High-quality factor quartz disc resonators have been fabricated with Q's ~50x greater (i.e., Q ~ 8 x 10^5) than silicon resonators of

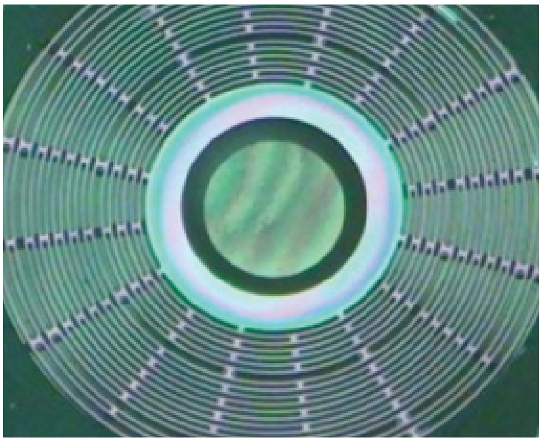


SEM micrograph of the NTJ IR detector and measurement of the detector response to illuminated light showing clear signal-to-noise ratio.

THE JPL MEMS GYROSCOPE EFFORT HAS BEEN AIMED AT ACHIEVING COMPARABLE PERFORMANCE TO OPTICAL GYROSCOPES WHILE RETAINING ALL THE ADVANTAGES OF MEMS DEVICES.



Vacuum-packaged CNVT using LCC-packages and solder reflow bonding technique.



Singulated device.

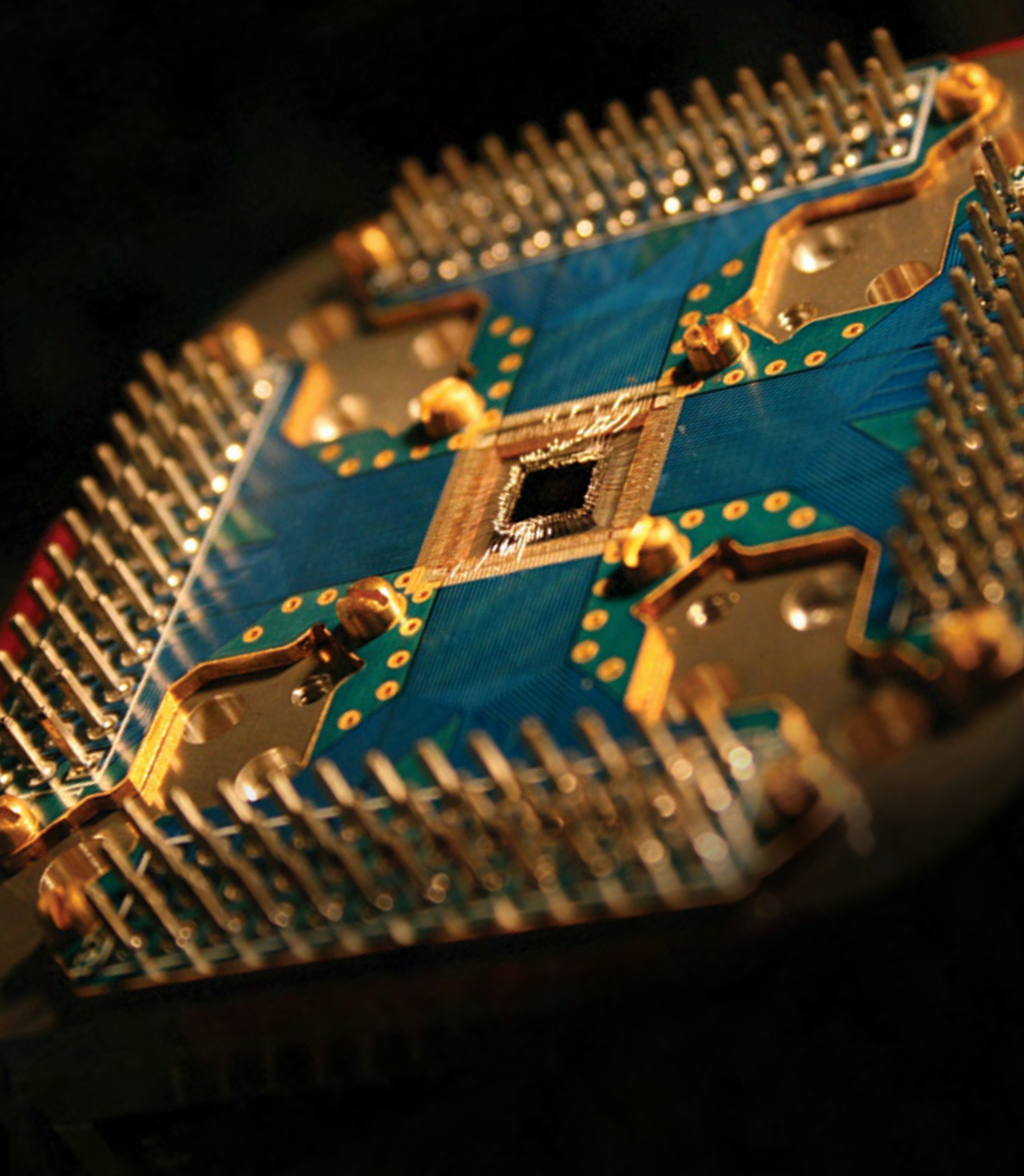
the same geometry, enabling increased device sensitivity of any resonant vibratory MEMS device. Using these resonators, the first operational amorphous quartz MEMS gyroscopes were assembled and tested at JPL. Also, high-vacuum packaging techniques were developed and demonstrated for these devices (see above). This work for has been a collaborative effort between JPL, the Boeing Co., Hughes Research Laboratory (HRL), University of California Los Angeles (UCLA), and Worcester Polytechnic Institute (WPI).

ANTENNA-COUPLED NTJ IR DETECTORS FOR HYPERSPECTRAL POLARIMETRIC FPA

The objective of this project is to develop and demonstrate proof-of-concept for novel antenna-coupled nano tunneling junction (NTJ)–based IR detectors, which will enable high-resolution hyperspectral and polarimetric infrared (IR) focal plane arrays (FPAs) without the need of optical filters and polarizer wheels and without cooling and with extremely small dissipation power.

The NTJ IR detectors operate under a new IR detection principle, zero-bias electronic rectification of nano Si-MOS (metal-oxide-semiconductor) diodes, in which the NTJ detectors utilize highly nonlinear current-voltage characteristics at zero-bias for rectification of incoming IR coupled through both wavelength- and polarization-agile antennas. Successful demonstration of the new IR detection mechanism will establish a key stepping stone toward uncooled, simultaneous hyperspectral and polarimetric sensing on a single FPA chip fabricated with Si-based technology, which can be easily scalable to a large IR FPAs.

2008 Highlights: Prototype antenna-coupled NTJ IR detectors have been developed and detector responses have been measured at room temperature using illumination from a heated tungsten filament within a small flashlight. The measured data indicated that the detector responds to the illuminated light with a clear signal-to-noise ratio. The project was carried out by JPL in collaboration with HRL Laboratories.



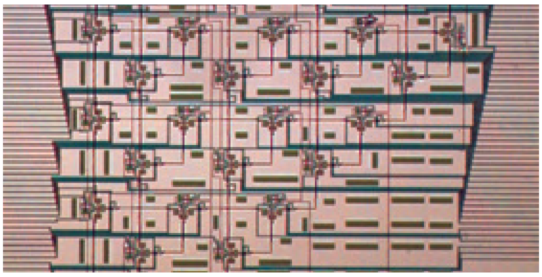
MDL fabricated chips into D-Wave processors have resulted in demonstrations of rudimentary quantum processing.

SUPERCONDUCTING INTEGRATED CIRCUITS

QUANTUM COMPUTING (QC) HOLDS THE PROMISE OF EXPONENTIALLY FASTER COMPUTING THAN IS POSSIBLE WITH TODAY'S CLASSICAL MACHINES. THIS WOULD ALLOW THE SOLUTION OF CURRENTLY INTRACTABLE PROBLEMS SUCH AS COMPLEX COMBINATORIAL OPTIMIZATION USED IN MISSION PLANNING, ENGINEERING DESIGN, ROBOTICS, AND ARTIFICIAL INTELLIGENCE.

Perhaps the most promising realizations of QC are based on superconducting devices operated at millikelvin temperatures. For over a decade, investigations of superconducting QC have focused on building, and understanding the properties of small populations of quantum bits (qubits). Problems such as qubit decoherence are closely related to problems encountered in the development of ultrasensitive superconducting detectors of electromagnetic radiation. Combining many years of experience in this area with more recent successes in advancing superconducting integrated circuit processing, makes JPL uniquely capable of fabricating, characterizing, and analyzing reliable submicrometer superconducting circuits with levels of complexity sufficient to move QC beyond device research and into processor development for practical applications.

For the past few years, MDL technologists have teamed with D-Wave Systems Inc. of Vancouver, Canada, to commercialize QC. D-Wave has pursued a novel approach to adiabatic quantum computing that allows combinatorial optimization problems to be mapped onto two dimensional arrays of superconducting quantum interference devices (SQUIDs). Exploitation of quantum effects in such processors promises dramatic speedup of calculations and improvement of solution accuracy.



Micrograph of the 28 qubit processor.

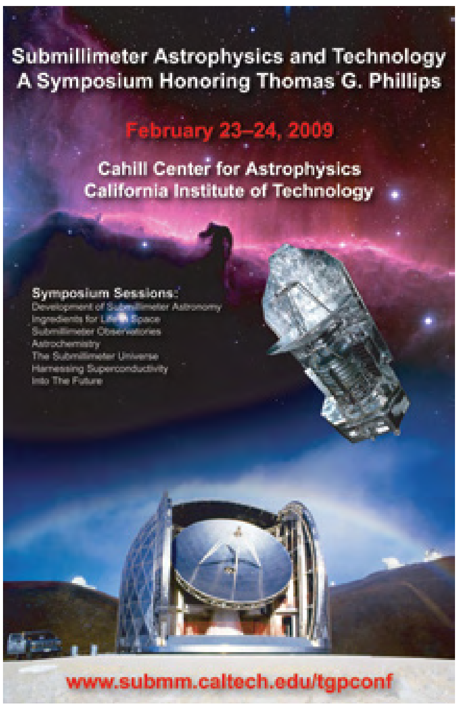
In the course of this collaboration, MDL has developed increasingly complex quantum chips, ranging from individual devices to coupled qubits to prototype quantum processors with up to 28 qubits. In addition, complex on-chip circuitry necessary for controlling increasingly larger qubit arrays has been demonstrated. By incorporating JPL chips into D-Waves processor designs, the collaboration has demonstrated rudimentary quantum processing.

This collaboration has not only benefited the commercial industry. Access to MDL's unique expertise in sub-μm Nb circuit fabrication has significantly advanced JPL's superconductor process development, allowed exploitation of new materials of interest for low-noise mK devices and circuits, developed flux qubits, and control circuitry that are potentially applicable in future JPL work.

Official conference photo (partial) for the Submillimeter Astrophysics and Technology Symposium held in honor of Thomas G. Phillips

CONFERENCES HOSTED BY JPL

SUBMILLIMETER ASTROPHYSICS AND TECHNOLOGY — A SYMPOSIUM HONORING THOMAS G. PHILLIPS



On February 23rd–24th, 2009, this two-day symposium discussed the latest advances in submillimeter astrophysics and technology, as well as celebrated and honored Thomas Phillips and his remarkable achievements and contributions.

With ALMA well into its construction phase, Herschel soon to be launched, and powerful new technologies, instruments, and projects on the horizon, astrophysics at submillimeter wavelengths is finally emerging from its early pioneering phase and is rapidly advancing toward the scientific forefront with an ever-accelerating stream of major new results. This is the legacy of Thomas Phillips, who for nearly four decades has been at the center of the most important developments in this field starting in the 1970s.

TOPICS COVERED:

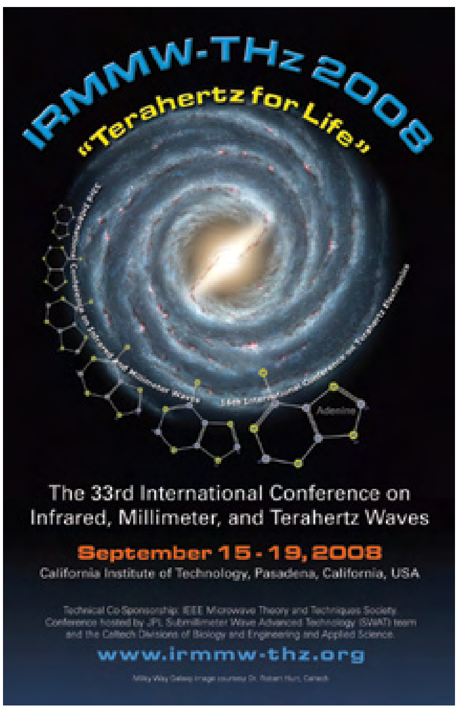
- Following the Water from 1969 to Herschel
- Water Vapor Observations from Ground-based Observatories
- Recent Developments at IRAM
- Submillimeter Heterodyne Arrays: From the CSO to APEX
- Millimeter Interferometric Observations of Galaxies: From Owens Valley to ALMA
- Negative Ions in Space: What They Are Telling Us
- The Horsehead Nebula: A Template Source for ISM Studies?
- Halogen-containing Molecules in the Interstellar Gas
- THz Spectroscopy in the Lab and at Telescopes
- Dissipative Structures of Interstellar Turbulence
- Probing the Magnetic Field with Molecular Ion Spectra
- Surveying Star Formation in the Galactic Plane with Bolocam
- Molecular Cooling as a Probe of Star Formation Physics
- Planck and the Submillimeter Explorer Science Goals
- Studies of Galaxy Clusters with Bolocam
- Warm Gas in the Early Universe: Broadband Spectroscopy with Z-Spec at the CSO
- The Birth of SIS Mixers
- Quantum Computing with Josephson Junctions
- SIS Receivers: From IRAM to the SMA
- The Promise of Herschel
- From HIFI to ALMA
- Future Detectors and Instruments

Conference Chairs: Bob Wilson; Al Wootten; Jim Moran; Peter Schilke; Ben Zuckerman; Jean Turner; Mike Wengler; Alain Omont; Jonas Zmuidzinas

Organizing Committee: Rena Becerra-Rasti, Caltech; Tom Bell, Caltech; Paul Goldsmith, NASA-JPL; Darek Lis, Caltech; Nick Scoville, Caltech; John Vaillancourt, Caltech; Jonas Zmuidzinas, Caltech/JPL, *Chair*.

CONFERENCES HOSTED BY JPL (CONT'D)

INTERNATIONAL CONFERENCE ON INFRARED, MILLIMETER, AND TERAHERTZ WAVES (IRMMW-THz)



IRMMW-THz, begun in 1974, is the oldest and largest continuous forum specifically devoted to the field of ultrahigh-frequency electronics and applications. The scope of the conference extends from millimeter-wave devices, components, and systems to far-infrared detectors and instruments. It encompasses micro- and nano-scale structures to large accelerators and Tokomaks and applications as diverse as space science, biology, and medicine. The 2008 IRMMW-THz conference was organized by Dr. Peter Siegel (Chair) and his co-workers from the Jet Propulsion Laboratory, California Institute of Technology. The conference venue was the picturesque campus of Caltech and it was held from September 15–19, 2008. Over 450 papers from 33 countries were presented during the conference.

TOPICS COVERED:

- New IR, THz, and MMW applications in Biology and Medicine
- IR, THz, and MMW Astronomy, Atmospheric, and Environmental Science Applications
- IR, THz, and MMW Spectroscopy, Instrumentation, and Material Properties
- IR, THz, and MMW Applications in Security and Defense
- IR, THz, and MMW Imaging and Imaging Applications
- IR, THz, and MMW Industrial Applications
- MMW and Submillimeter-Wave Radar and Communications
- Ultrafast Measurements in Chemistry and Physics
- Terahertz Instruments: both Frequency and Time Domain
- Transmission Lines, Waveguides, and Antennas
- Gyro-Oscillators and Amplifiers; Plasma Diagnostics
- Free-Electron Lasers and Synchrotron Radiation
- Novel Devices and Components for IR, THz, and MMW applications
- Modelling and Analysis Techniques
- IR, THz, and MMW Sources, Detectors, and Receivers
- High-Power, Nonlinear, and Optoelectronic Effects at THz Frequencies
- IR, THz, and MMW Future Applications, Markets, and Directions

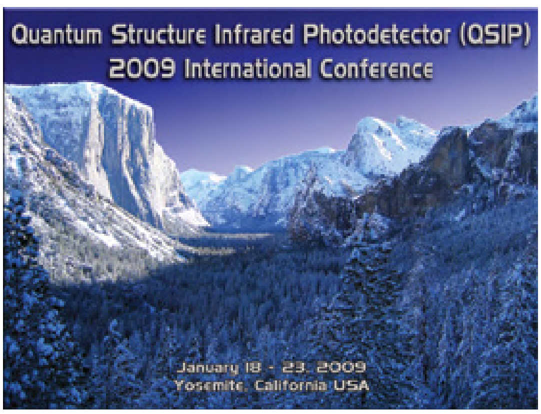
2008 Honorary Chair: Kenneth J. Button

2008 Conference Chair: Peter H. Siegel

International Organizing Committee: Trevor Bird, Australia; Martyn Chamberlain, UK; Jean Louis Coutaz, France; Bruce Danly, USA; Gian Piero Gallerano, Italy; TV George, USA; Armand Hadni, France; Qing Hu, USA; Martin Koch, Germany; Jean Leotin, France; Alexander Litvak, Russia; Neville Luhmann, USA; Robert Miles, UK; Dan Mittleman, USA; Koji Mizuno, Japan (Chair); Mitsuhiro Motokawa, Japan; George Neil, USA; Gregory Nusinovich, USA; Michael von Ortenberg, Germany; Terry Parker, UK; Kiyomi Sakai, Japan; Xuechu Shen, China; Liu Shenggang, China; Peter H. Siegel, USA (Vice Chair); Richard Temkin, USA; Manfred Thumm, Germany; Minh Tran, Switzerland; Ken Wood, UK; Xi-Cheng Zhang, USA.

MICRODEVICES LABORATORY SCIENTISTS ORGANIZED AND HOSTED THREE INTERNATIONAL CONFERENCES IN THE PAST YEAR.

QUANTUM STRUCTURE INFRARED PHOTODETECTOR (QSIP) 2009 INTERNATIONAL CONFERENCE



Development in quantum structure–based infrared photodetector technologies, including quantum wells, dots, superlattices, and novel heterostructures, over the last two decades has led to the realization of high-performance infrared detectors, large-format focal plane arrays, and infrared cameras that are now readily available commercially through several manufacturers. The QSIP 2009 conference aimed to bring together scientists, engineers, industrial collaborators, students, and users to discuss recent advances in this field. The conference provided an international forum for attendees to present and discuss new progress in device physics, materials growth and processing issues, focal plane array development and characterization, as well as commercialization and applications of QSIP technologies. The conference also explored the benefits and drawbacks of these technologies, and clarify their role in the competitive market of thermal imaging technology. Dr. Paul Dimotakis (JPL Chief Technologist), Ms. Barbara McQuiston (Director DARPA Strategic Technology Office), Dr. Meimei Tidrow (Missile Defense Agency), and Dr. Fenner Milton (Director Army Night Vision Electronic Sensor Directorate) served in the advisory committee and gave the key note speeches.

TOPICS COVERED:

- Novel Device Concepts
- Strained Layer Superlattice (SLS) Detector
- Dual-band SLS
- Heterojunction Barrier Detector
- Quantum-Well Infrared Photodetector (QWIP)
- Multi-Color QWIP
- Quantum Dot Infrared Photodetector (QDIP)
- Readout integrated circuits for infrared focal plane arrays
- Alternative Material Systems
- Infrared Applications

Organizing Committee: S. Gunapala, NASA-JPL, USA, *Chair*; H. C. Liu, NRC, Canada, *Co-Chair*; M.Razeghi Northwestern University, USA, *Co-Chair*; S. Bandara US Army, NVESD; C. Hill, NASA-JPL; D. Ting, NASA-JPL; J. Zmuidzinas, Caltech, USA.

Program Committee: J. Andersson, Acreo AB, Sweden; P. Bois, Thales, France; G. Brown, AFRL, USA; V. Berger, University of Paris, France; A. Carbone, Politecnico di Torino, Italy; Y. C. Chang, Academia Sinica, Taiwan; K. K. Choi, ARL, USA; E. Costard, Thales, France; J. Devitt, L3, USA; E. Aifer, NRL, USA; L. Faraone, University of Western Australia, Australia; M. Henini, University of Nottingham, UK; C. Jagadish, ANU, Australia; M. Jhabvala, NASA-GSFC, USA; S. Jost, BAE, USA; D. Kemberling, QWIP Technologies, USA; M. Kimata, Ritsumeikan University, Japan; S. Krishna, University of New Mexico, USA; W. Lu Shanghai, Institute of Technical Physics, China; J. Meyer, NRL, USA; J. Pellegrino, NVESD, USA; U. Perera, Georgia State University, USA; R. Rehm, Fraunhofer Institute, Germany; D. Rhiger, Raytheon, USA; V. Ryzhii, University of Aizu, Japan; G. Sarusi, elop Industries, Israel; J. Scott, Lockheed Martin, USA; H. Schneider, Forschungszentrum Rossendorf, Germany; M. Strojnik, Centro de Investigaciones en Optica, Mexico; M. Sundaram, QmagiQ, USA; W. Wang, Columbia University, USA; L. Wilson, University of Sheffield, UK; P. Wijewarnasuriya, ARL, USA; J. Woolaway, FLIR Indigo, USA; J. Zahn, Cantronic Systems, Canada; L. Zheng, IDA, USA.

Advisory Committee: D. Cardimona, AFRL, USA; T. Cwik, NASA-JPL, USA; P. Dimotakis, Caltech, USA; J. Durek, DARPA; A. Kapadia, U.S. Army, PEO STRI; W. Langer, NASA-JPL, USA; P. LeVan, AFRL, USA; B. McQuiston, DARPA; F. Milton, NVESD, USA; M. Tidrow, MDA, USA; M. Vuong, U.S. Army, PEO STRI.

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NEW TECHNOLOGY REPORT AND PATENTS

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MDL EQUIPMENT COMPLEMENT

MATERIAL DEPOSITION

- Thermal Evaporators (6)
- Electron-Beam Evaporators (7)
- Ultrahigh vacuum (UHV) Sputtering Systems for dielectrics and metals (3)
- Ultrahigh vacuum (UHV) Sputtering Systems for superconducting materials (2)
- Plasma-Enhanced Chemical Vapor Deposition (PECVD) Systems for doped and undoped amorphous Silicon (2)
- Plasma-Enhanced Chemical Vapor Deposition (PECVD) System 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
- Low-Pressure Chemical Vapor Deposition (LPCVD) System (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 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 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.
- 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)
- 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 ICP Chlorine RIE
- Oxford Inductively Coupled Plasma (ICP) RIE

WET ETCHING & 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 (8)
- 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 Analyzer
- 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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