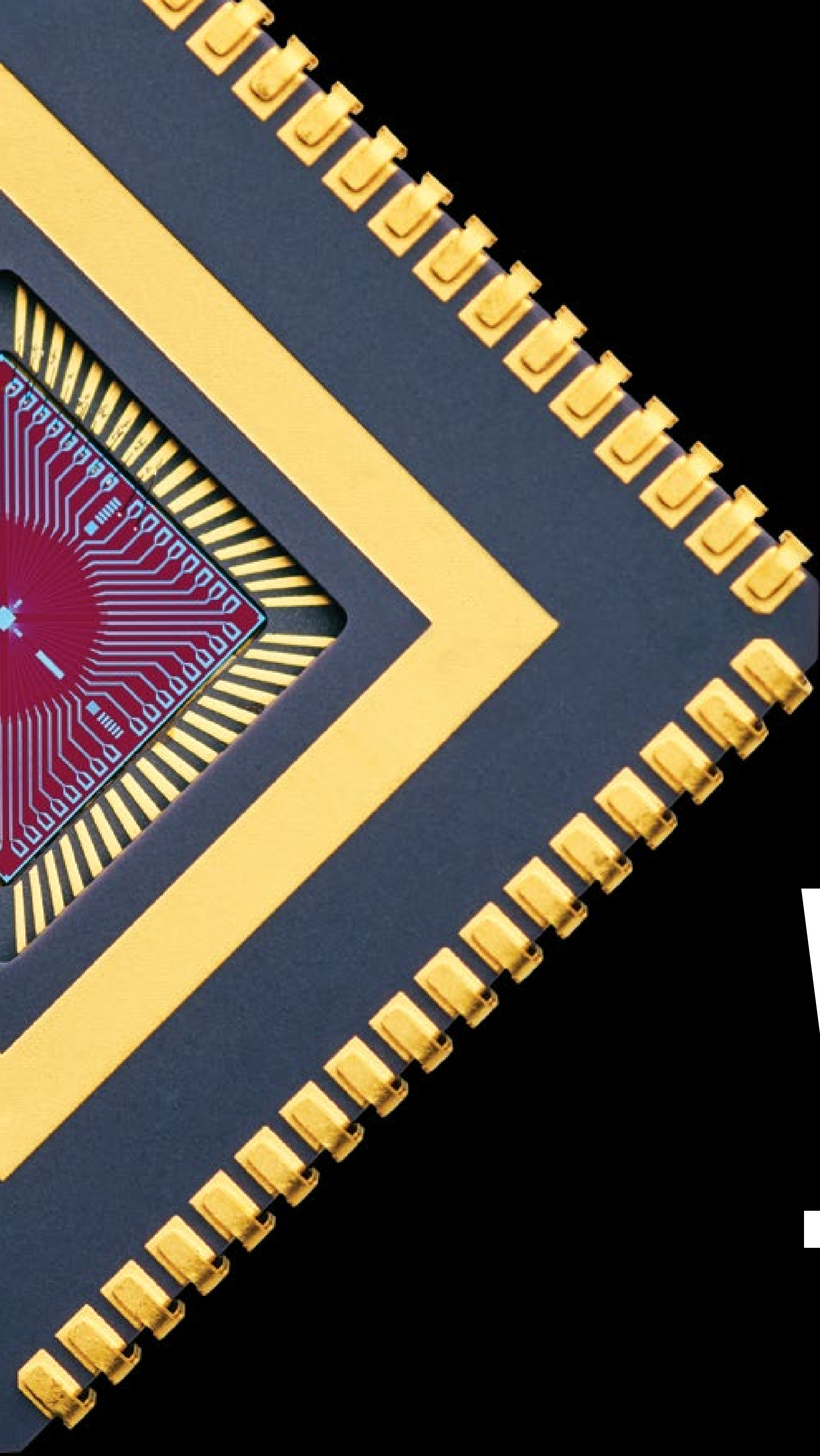


National Aeronautics and Space Administration

WE'RE OUT THERE

MICRODEVICES LABORATORY

2017–2018 ANNUAL REPORT

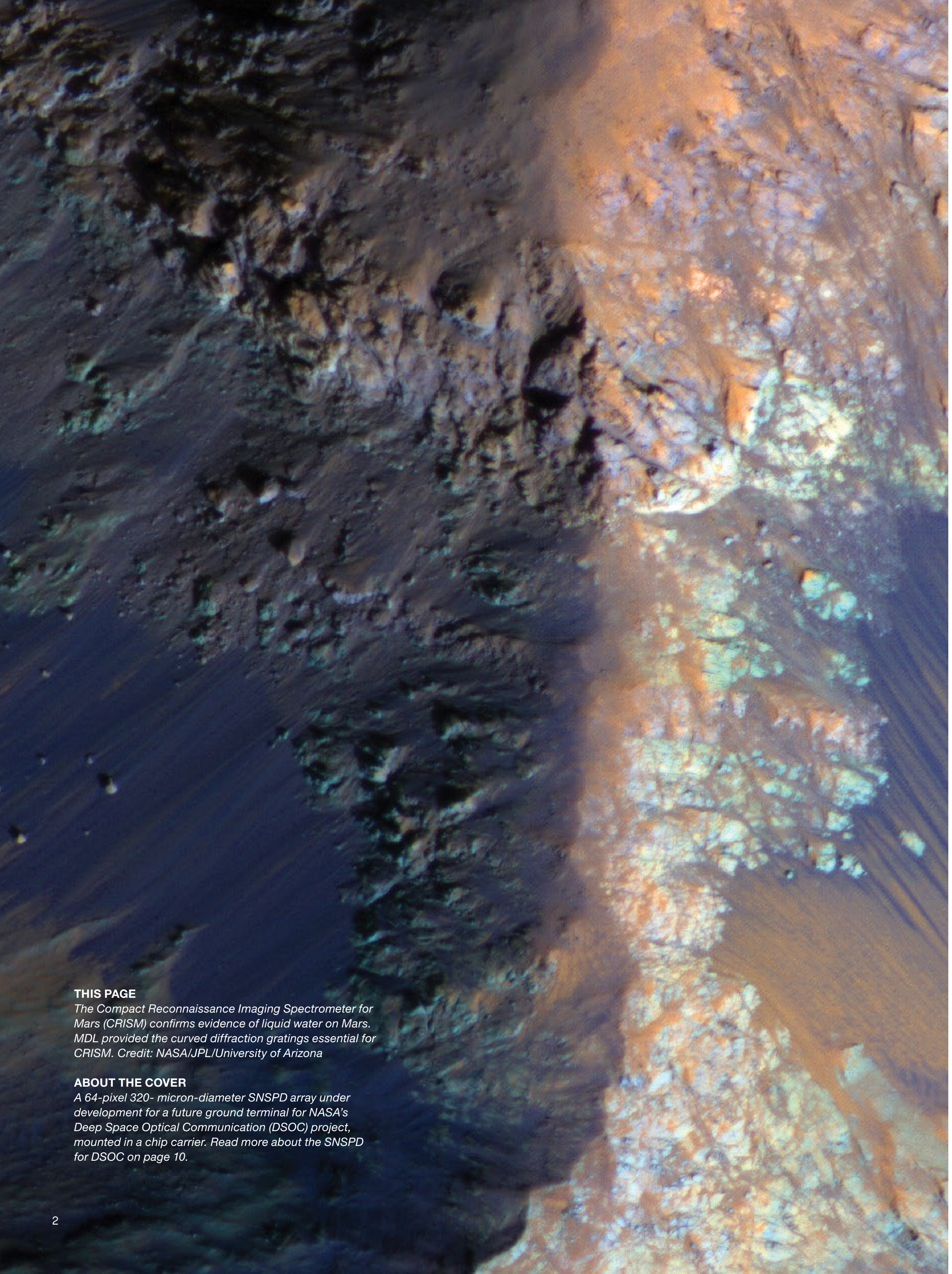
Jet Propulsion Laboratory

WE BREAK NEW GROUND

TODAY, TOMORROW, AND BEYOND

At JPL's Microdevices Laboratory (MDL), we dare mighty (small) things. Since 1989, the MDL has been a critical player in JPL's dedicated efforts to create and deliver high-risk, high-payoff micro- and nanoscale technology for NASA's planetary, astrophysics, and Earth science missions. From the beginning, MDL has cultivated an environment that values and promotes leadership, vision, and innovation while improving and implementing new technologies that drive NASA's ongoing quest to probe the mysteries of the universe. From breaking new ground through unique strategies in the lab to enabling the latest missions to probe the cosmos like never before, MDL technology is out there helping to answer big questions about how stars and galaxies form, the possibility of life beyond our planet, the evolution of other worlds, and the health of Earth.

Credit: NASA



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The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) confirms evidence of liquid water on Mars. MDL provided the curved diffraction gratings essential for CRISM. Credit: NASA/JPL/University of Arizona

ABOUT THE COVER
A 64-pixel 320- micron-diameter SNSPD array under development for a future ground terminal for NASA's Deep Space Optical Communication (DSOC) project, mounted in a chip carrier. Read more about the SNSPD for DSOC on page 10.

JPL ASSOCIATE DIRECTOR FOR STRATEGIC INTEGRATION

Consistent with NASA's 2018 Strategic Plan, the JPL 2018 Strategic Implementation Plan calls for the continued investment and leadership in robotic space exploration for the benefit of humankind. The Micro-devices Laboratory (MDL) at JPL has played a leadership role over the past 25 years in inventing, developing, and delivering unique microdevices that have enabled a broad set of NASA missions. Currently MDL-developed devices are contributing to JWST, Mars 2020, Europa Clipper, ECOSTRESS, ISS Spacecraft Atmosphere Monitor, and more than 20 other NASA missions and projects. As we look to the future, JPL will continue its strong support and investment in MDL's people, facilities, and research, and continue to build on this exceptional track record to ensure that future missions benefit from this unique capability for many years to come.

DAVID GALLAGHER
Associate Director for Strategic Integration, JPL

MDL DIRECTOR

This past year has been an exceptionally strong one for the Microdevices Laboratory (MDL), with the delivery of enabling devices for a diverse set of NASA space missions as well as the selection of new projects that will use MDL technologies and devices. Thanks to the efforts of the technical staff, there are now more than 20 MDL devices included in NASA missions planned for space flight in the next few years. These devices contribute to JPL Directorates including Solar System Exploration, instruments for Mars Exploration, Astronomy and Physics, Earth Science and Technology, and Interplanetary Network future optical communications. MDL continues to excel as it fulfills its charter as a facility to create, develop, deliver, and integrate novel microdevices and critical microdevice technologies that enable instruments and missions for JPL and NASA. MDL's sustained success is highlighted through the innovative devices, technologies, and capabilities described in this annual report. Looking forward, MDL is commit-ted to delivering the current devices for planned space missions and, equally as important, investing now in new technologies, capabilities, and people to invent, develop, and deliver the next generation of enabling devices for future JPL and NASA projects and missions.

ROBERT O. GREEN
Director, JPL Microdevices Laboratory

EARTH'S MOON
View of a crescent moon rising and the cusp of Earth's atmosphere. The dominant gases and particles in each layer of the atmosphere act as prisms, revealing distinct colors.

Credit: NASA

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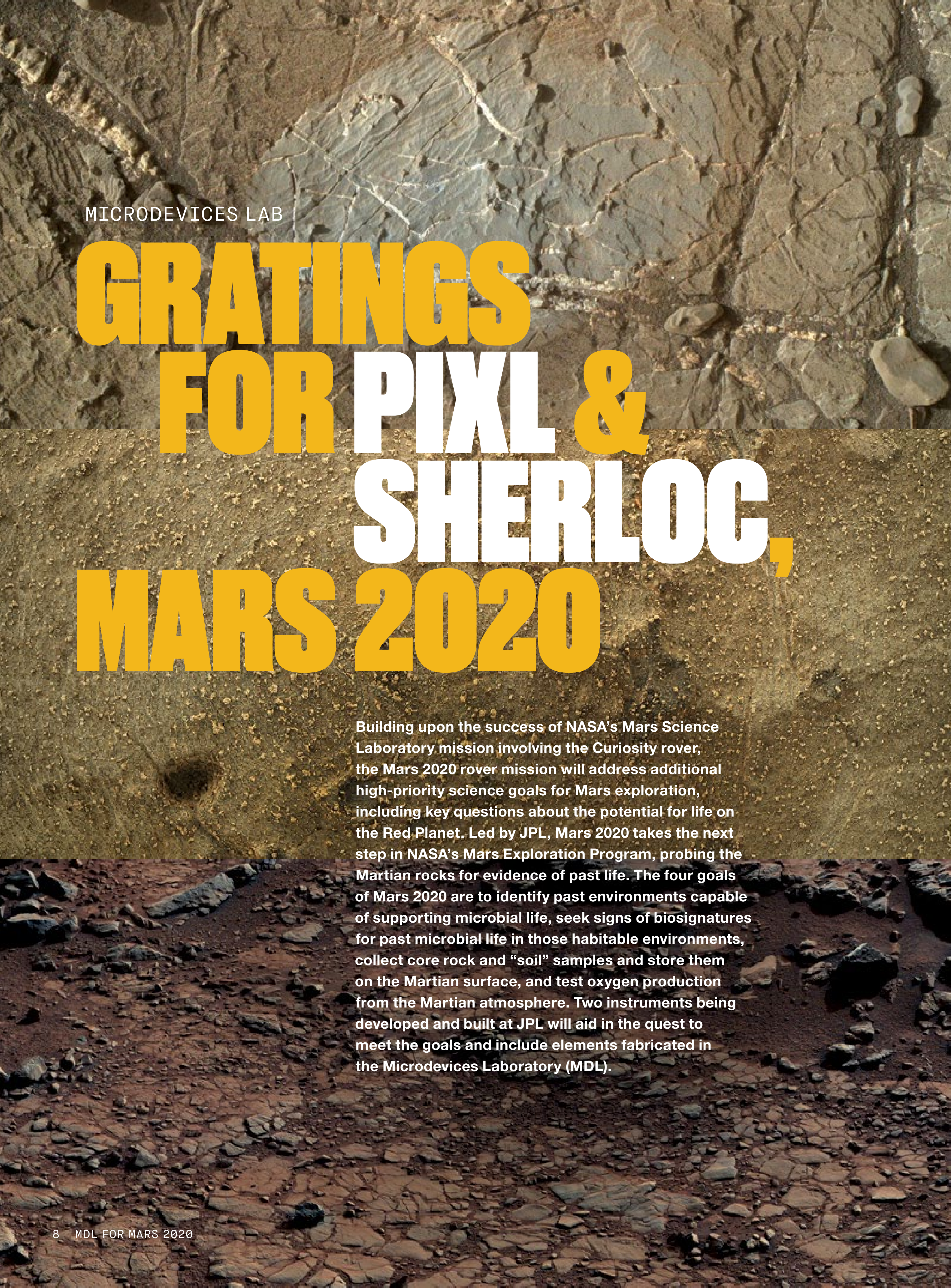
TODAY'S TECHNOLOGIES ARE TOMORROW'S MISSIONS

WE'RE OUT THERE

The evidence of the Microdevices Laboratory's (MDL) achievements can be seen in the numerous cutting-edge devices and components that have flown in space, enabling new science measurements and novel investigations for JPL and NASA. Whether the goal is to explore how Earth is changing, to investigate the possibility of past or present life on the planets or their moons in our solar system, to find extra-solar Earth-like planets, or to study the formation and evolution of our universe, MDL plays a crucial role in advancing these missions. From ground-based telescopes and atmospheric balloons, to planetary rovers and instruments that assemble in space, innovative MDL technology is out there.



MICRODEVICES LAB

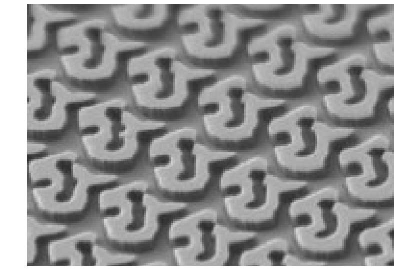
GRATINGS FOR PIXL & SHERLOC, MARS 2020

Building upon the success of NASA's Mars Science Laboratory mission involving the Curiosity rover, the Mars 2020 rover mission will address additional high-priority science goals for Mars exploration, including key questions about the potential for life on the Red Planet. Led by JPL, Mars 2020 takes the next step in NASA's Mars Exploration Program, probing the Martian rocks for evidence of past life. The four goals of Mars 2020 are to identify past environments capable of supporting microbial life, seek signs of biosignatures for past microbial life in those habitable environments, collect core rock and "soil" samples and store them on the Martian surface, and test oxygen production from the Martian atmosphere. Two instruments being developed and built at JPL will aid in the quest to meet the goals and include elements fabricated in the Microdevices Laboratory (MDL).

SHERLOC

Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals (SHERLOC) will use an ultraviolet laser to illuminate a tiny area of Martian soil. A deep ultraviolet spectrometer will analyze Raman scattering and material fluorescence, which will enable non-contact, spatially resolved, and highly sensitive detection and characterization of organics and minerals in the Martian surface and near subsurface. This may provide evidence of the Martian surface's past aqueous history and may also detect the presence and preservation of potential biosignatures. In support of SHERLOC, MDL is fabricating gratings by electron-beam lithography for the Raman and fluorescence spectrometer (below). To provide the required spectral resolution, the grating has a very fine pitch, on the order of 4000 grooves/mm, and the groove profile was optimized to achieve maximum diffracted signal. These fabricated gratings have been measured to produce near the theoretical maximum diffraction efficiency at the 248.6 nm operating wavelength.

SHERLOC'S principal investigator is Luther Beegle. The principal investigator for the grating is Dan Wilson at MDL.



SEM OF GRATING
Scanning electron microscope (SEM) image of the seven-by-seven spot array grating

SPOT ARRAY
Seven-by-seven spot array produced by 830 nm infrared laser transmitted through the above CGH grating

PIXL

The Planetary Instrument for X-ray Lithochemistry (PIXL) is an X-ray fluorescence instrument that will examine fine scale elemental chemistry in Martian rocks and soils. The instrument's sub-millimeter resolution will allow scientists to pinpoint tiny features such as individual grains, spherules, veins, and crystals, and examine their elemental makeup. Previous Martian X-ray spectrometers could only measure the bulk composition of samples. For example, the X-ray spectrometer on the Mars Science Laboratory's Curiosity rover is limited to a 17 mm diameter sample area. PIXL will scan a 100 micron X-ray beam in 100 micron steps over a 25 mm square area. In order to precisely map the X-ray beam location within the high-resolution optical image, PIXL will use an optical fiducial subsystem (OFS) co-aligned with the X-ray beam. A key element of the OFS are two micro-optic spot array generators that produce evenly spaced grids of laser spots. These spot array generators are transmissive computer-generated holo-gram (CGH) gratings. The CGH gratings were designed, patterned by electron-beam lithography, and plasma-etched into glass at MDL. Each unit cell of the two-dimensional CGH grating is made up of submicron square pixels, first electron-beam patterned into a chrome stencil layer, and then transfer-etched to the proper depth in glass. After the chrome etch mask is removed, the remaining surface relief pattern imparts a phase pattern on the laser beam, causing it to diffract into an array of spots with near equal intensity. Gratings for three-by-five and seven-by-seven spot arrays have been fabricated (see above).

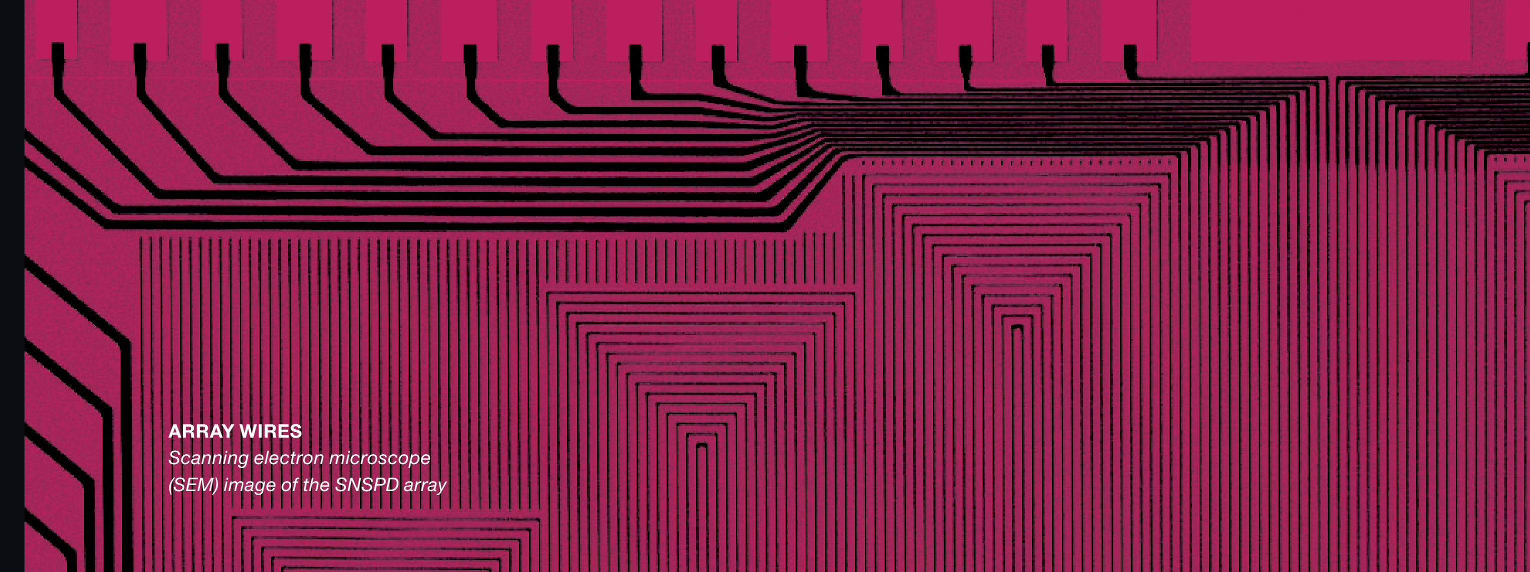
PIXL'S principal investigator is Abigail Allwood. The principal investigator for the grating is Dan Wilson at MDL.

MICRODEVICES LAB

SUPERCONDUCTING NANOWIRE SINGLE PHOTON DETECTORS FOR DSOC

As instruments to explore the solar system and the cosmos increase in complexity, and the reach of human space exploration expands toward Mars, data rate limitations of conventional radio communications place serious constraints on the design of future missions. On Earth, laser communication networks over glass fibers have transformed our society, enabling vast amounts of data to be transferred around the globe in the blink of an eye. But repeating the same feat for a spacecraft in deep space is no easy trick. A laser spot fired from Mars will be hundreds of kilometers wide when it reaches Earth, so even the largest telescopes would only receive signals at the single-photon level. Special codes must be used to maximize the efficiency with which information is sent on each photon, and the world's most high-performance single photon detectors must be used on the ground. The Microdevices Laboratory (MDL) has recently developed state-of-the-art superconducting ground detectors for the first demonstration of laser communication ever to take place from deep space, the NASA Deep Space Optical Communication (DSOC) project. DSOC plans to downlink data from a JPL-built laser transmitter aboard the Psyche spacecraft at 267 Mbps from 0.2 AU, and over 1 Mbps at 2.7 AU. In a future optical Deep Space Network, laser communication promises to increase data rates by 10 to 100 times compared to Ka-band radio, with the same mass and power on the spacecraft. To meet the ambitious goals of the DSOC project, MDL had to develop a superconducting ground detector with 100 times the active area and 10 times the maximum count rate of a conventional state-of-the-art single photon detector, all while maintaining high efficiency and sub-100 picosecond timing resolution.

Credit: Phillip Colla / Oceanlight.com

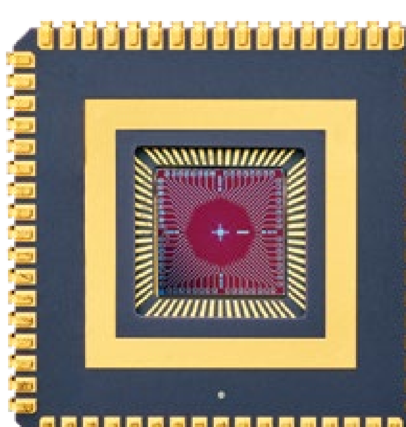


ARRAY WIRES
Scanning electron microscope (SEM) image of the SNSPD array

Superconducting Nanowire Single Photon Detectors (SNSPD) are the highest performing detectors available from the ultraviolet to the mid-infrared. Since 2005, MDL has been a world leader in the development of this unique technology, and currently holds world records for SNSPD detection efficiency, time resolution, active area, and dark counts. While design, nanofabrication, and testing of SNSPD devices is all performed at JPL, the technology development process for these devices has been highly interdisciplinary, with fruitful collaborations at the National Institute of Standards and Technology, the Massachusetts Institute of Technology, and Caltech. SNSPDs are a key technology for deep space optical communication and JPL SNSPD arrays were fielded on the ground in the Lunar Laser Communication Demonstration (LLCD) in 2013. Next, they are planned for the ground terminal of the Deep Space Optical Communication (DSOC) project, which is scheduled for launch aboard the Psyche spacecraft. The DSOC project would be the first demonstration of laser communication from beyond lunar orbit and would extend the range of laser communication demonstrations by a factor of 1000 from what was achieved in LLCD. To receive the faint signals from the laser transmitter on its cruise toward the asteroid belt, MDL has developed a unique 64-pixel SNSPD array sensor capable of time-tagging individual photon arrivals to sub-100 picosecond accuracy at count rates in excess of a billion counts per second. A cryogenic detector instrument based around this device will be fielded at the five meter ground telescope at Palomar Observatory in Southern California for use in the DSOC ground terminal. Delivery of the DSOC flight and ground terminals is expected in 2021, with the spacecraft launch to occur in the summer of 2022. During the spacecraft's cruise phase, DSOC will demonstrate the viability of laser communication links at a variety of ranges up to 2.7 AU, beyond Mars's farthest range. With DSOC, the first demonstration of optical communication from deep space will place JPL in a strategic position to lead the Deep Space Network into the laser communication era.

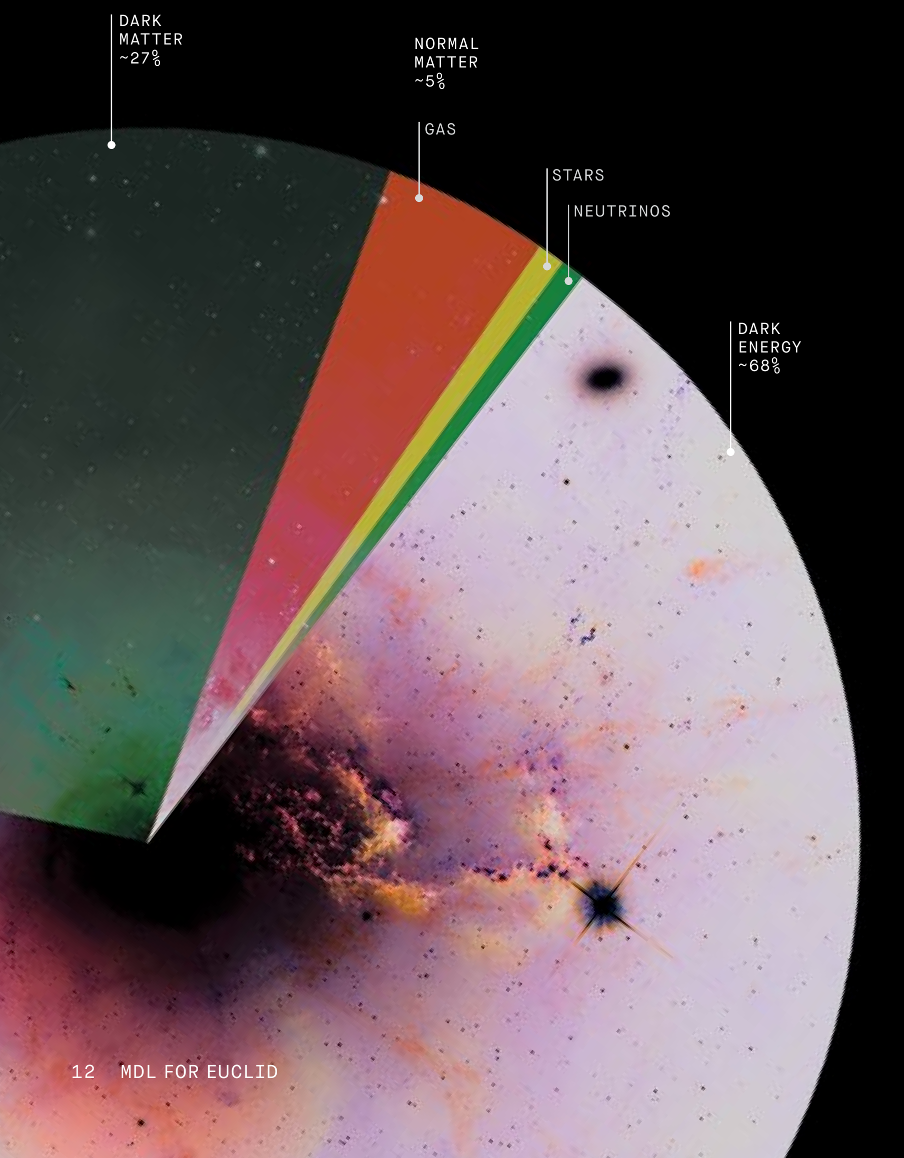
Project manager for the DSOC mission is Bill Klipstein at JPL. Abi Biswas at JPL is the project technologist. Principal investigator for the SNSPD is Matt Shaw at MDL.

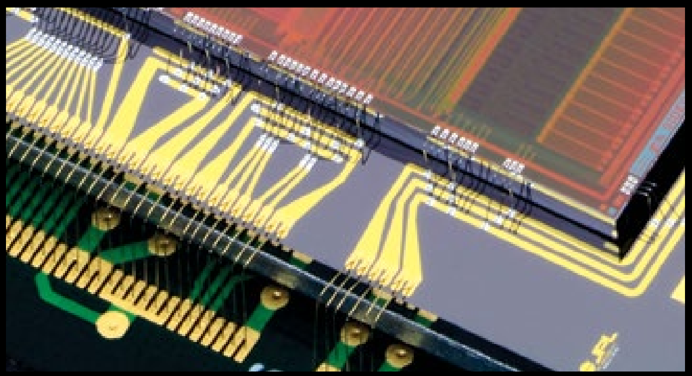
SNSPD CHIP
A 64-pixel 320- micron-diameter SNSPD array under development for a future ground terminal for NASA's Deep Space Optical Communication (DSOC) project, mounted in a chip carrier



CRYOGENIC ELECTRONICS PACKAGING FOR EUCLID

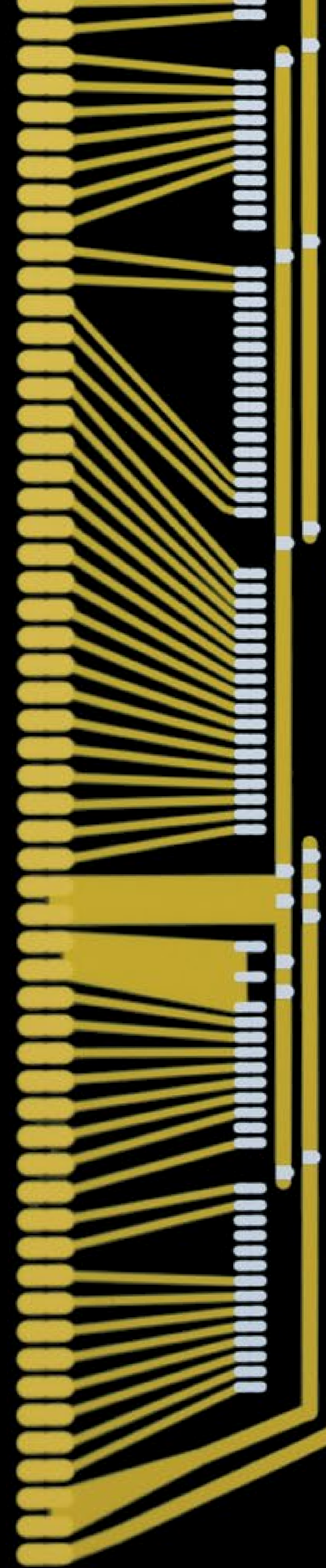
In 1998, the Hubble Space Telescope—with the help of ground-based telescopes—made a series of observations of very distant supernovae that showed that, a long time ago, the universe was actually expanding more slowly than it is today. This contradicted the common idea that the expansion of the universe had been slowing due to gravity and rather gave evidence that it has been accelerating. Theorists still can't explain why this is happening, but they call the cause dark energy. This mysterious dark energy makes up roughly 68 percent of the universe. Dark matter, which is also puzzling, makes up about another 27 percent and the rest—less than 5 percent—is made up of the normal matter that makes up everything we can see in the universe, like stars, planets, galaxies, and us. The Euclid mission, to be launched in 2021, is designed to provide an unprecedented look at this "dark side" of the universe. The Microdevices Laboratory (MDL) will aid in this exploration of these curious components of the cosmos by manufacturing a key piece of the integrated circuits for the spacecraft's telescope. "Euclid will be a powerful tool for understanding the distribution of dark matter in the universe and how that distribution has been influenced by dark energy over the last 10 billion years," says JPL's Jason Rhodes, observational cosmologist and a NASA representative on the Euclid science team.





CHIP ON BOARD
Left. Close up view of aluminum wirebonds from the ASIC to the silicon fan out and gold wire bond from the silicon fan out to the printed wiring board

Right. Edge detail of the fan out board



Euclid is a European Space Agency (ESA)–led mission to orbit a telescope at the L2 Sun-Earth Lagrangian point in order to do a comprehensive survey of galaxies over about one-third of the sky. This survey will be used to develop a map of mass distribution in the universe, which will then allow powerful tests of cosmological theories. The focal plane of the Euclid telescope contains a visible instrument and a Near Infrared Spectro-Photometer (NISP). JPL/NASA is providing 16 "sensor chip systems," composed of infrared detectors, cables, and cryogenic electronics, to ESA and the NISP team in France. The detector arrays and application-specific integrated circuit (ASIC) chip used in the cryogenics electronics provided by Teledyne Imaging Systems in Camarillo, California. The NASA team, including engineers at JPL and the Goddard Space Flight Center, have developed a package for the ASIC that works at cryogenic temperatures with high reliability. The package is based on chip-on-board architectures used for JPL's Spectral and Photometric Imaging Receiver (SPIRE), Goddard's Thermal Infrared Sensor (TIRS), and Goddard's Microshutter Arrays to launch on the James Webb Space Telescope, all of which were operated successfully in space at deep cryogenic temperatures well below 130 K, the operating temperature required for the Euclid ASIC.

MDL is manufacturing flight silicon fan out boards for the new ASIC package. This silicon fan out is necessary to interface the fine wire bond pitch on the ASIC to a wider wire bond pitch on the printed circuit boards. The silicon fan out fabrication leverages a recently purchased EX6 stepper photo-lithography system to produce all units quickly and with near 100 percent yield. JPL is also performing the epoxy attach of the silicon components to the metal housing and the fine wire bonding of the fan out to the wiring board and from the ASIC to the fan out. Both processes have been developed specially by JPL/NASA to survive thermal cycling to cryogenic temperatures. These processes are directly applicable to future electronics to be built for missions to moons of outer planets such as Europa, Enceladus, and Titan, and for cutting edge, industry-leading "Earth bound" technologies such as superconducting quantum computing.

Giuseppe Racca is the Euclid project manager for the ESA, René Laureijs is the Euclid project scientist, and Jason Rhodes is the NASA representative on the Euclid science team. Technical lead for the Cryogenic Electronics Packaging is Warren Holmes at MDL.

MICRODEVICES LAB

LASER-BASED INSTRUMENT FOR COMBUSTION PRODUCT MONITORING

Fires can happen anywhere—even in space. So, for the astronauts who live and work there, it is critical to understand how fire spreads in a microgravity environment and how to manage it safely. NASA has conducted studies as part of the space shuttle and International Space Station (ISS) programs, but these have been limited in size and scope due to the risks involved for astronauts. Now, new experiments are helping researchers better understand spacecraft fires on a larger scale. The Spacecraft Fire Experiment, known as Saffire, is a series of tests on unmanned supply vehicles returning from the ISS. The Microdevices Laboratory (MDL) is developing a laser-based instrument to measure the gases that the test fires produce.

Fire experiments in realistic environments help engineers understand risks to human health and formulate protective measures. Fire hazards are particularly dangerous in the confines of human-occupied spacecraft, yet there are limited opportunities to test fire protection systems in orbit. Led by NASA's Glenn Research Center, Saffire consists of a series of full-scale combustion tests performed aboard automated transfer vehicles during the return trip from the International Space Station. Saffire enables the study of flame growth, flammability limits, and other important characteristics within the unique low-gravity environment of space, without risking the safety of astronauts.

Engineers from MDL have developed the Combustion Product Monitor (CPM) instrument to measure specific fire products during a future Saffire flight. CPM uses compact semiconductor lasers to probe the abundance of carbon monoxide, carbon dioxide, and oxygen, as well as trace amounts of hydrogen fluoride, hydrogen chloride, and hydrogen cyanide, as these gases are produced (or consumed) during a combustion event. The JPL CPM instrument is expected to launch aboard an Orbital Sciences Cygnus resupply vehicle in 2020. Fire experiments will be conducted after the spacecraft departs from the International Space Station and prior to reentering Earth's atmosphere.

In addition to supporting the near-term objectives of Saffire, the CPM instrument is a valuable testbed for laser spectroscopy sensors designed to support human spaceflight operations. Laser-based gas sensors can produce accurate concentration measurements over a broad range of pressures and temperatures and are capable of thousands of hours of maintenance-free operation. Such a robust sensor platform will be essential as humans push beyond low Earth orbit to explore deep space.

CYGNUS
Orbital Supply Vehicle
Credit: NASA

The Saffire program is led by Dr. Gary Ruff, at the NASA Glenn Research Center in Cleveland, Ohio. The Combustion Product Monitor project at JPL is led by MDL's Ryan Briggs.

THE COMPLETED COMBUSTION PRODUCT MONITOR INSTRUMENT

HELIX OF NEBULA *Venus crosses the line of sight between the sun and Earth four times every 243 years in pairs separated by eight years.*

Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams

MICRODEVICES LAB

HIGH EFFICIENCY DETECTORS FOR SPARCS

In the search for extraterrestrial signs of life, many researchers are focusing on exoplanets—or planets that exist beyond our solar system—so far away that they are undetectable using current technology. Flagship mission concepts, such as the Habitable Exoplanet Imaging Mission (HabEx) or the Wide-Field Infrared Survey Telescope (WFIRST), will use large telescopes to directly image and characterize exoplanets by masking starlight. Interpretation of data for assessing the habitability of the exoplanet from these large telescopes requires a complete view of nearby star ultraviolet activity. A new small mission called the Star-Planet Activity Research CubeSat, or SPARCS, will do just that in 2021. The goal of SPARCS is to take a step back and examine the flares and other stellar activities of red dwarf stars, which are less than half the size of our sun and with 1 percent of its brightness. There are about 40 billion red dwarf stars in the Milky Way galaxy, and the mission—with the help of unique ultraviolet sensors developed by the Microdevices Laboratory (MDL)—will provide insight into habitable star systems and give researchers clues about how to interpret exoplanet data from bigger space telescopes.

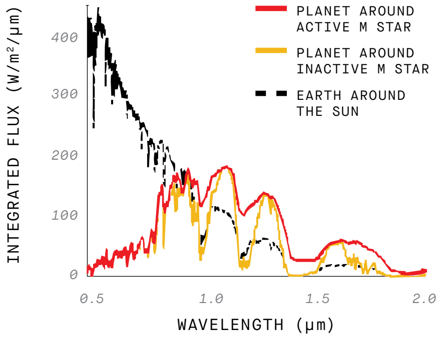
In 2018, the SPARCS mission was one of only two CubeSat missions selected in astrophysics by the Astronomy and Physics Research and Analysis program, which manages the Astrophysics CubeSats and suborbital missions for NASA. SPARCS would be the first mission to provide dedicated, long-duration ultraviolet (UV) observations of red dwarf stars. These measurements are crucial to interpreting observations of planetary atmospheres around low-mass stars. Astrophysics missions have been more challenging to fit the form factor of small CubeSats because they typically depend on large aperture telescopes. With innovations in high-efficiency silicon UV detectors, where the need for high voltage and bulky detectors is eliminated, astrophysics UV CubeSat missions are becoming a reality. SPARCS achieves this in a six-unit CubeSat the size of a cereal box by using a small telescope and high-performance UV camera to help understand exoplanet habitability potential through ultraviolet observations. SPARCS will make UV observations of the stars and study the effect that their ultraviolet activity might have on the nearby habitable zone planets' atmospheric signatures and therefore may affect the assessment of the exoplanet habitability.

SPARCS is a collaborative effort between Arizona State University and JPL. JPL is responsible for delivery of the SPARCam, an ultraviolet camera with two channels in the far ultraviolet (FUV) and near ultraviolet (NUV). The heart of the SPARCam is the detectors with a response tailored at MDL to optimize the SPARCS science return by maximizing the sensitivity to the desired spectral band while rejecting the out-of-band light—a breakthrough for silicon detectors.

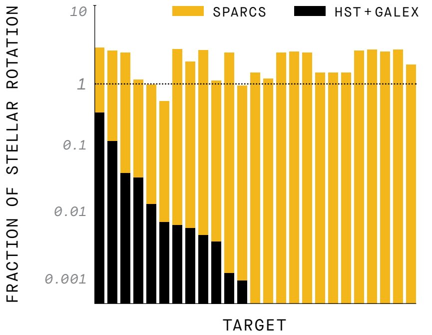
Silicon detectors are used universally on NASA missions, creating images that are crucial for the entry, descent, and landing process, as well as providing images for necessary context in science measurements. Image-tube-based detectors have been used extensively in the ultraviolet spectral range in the past; however, they are bulky, have low sensitivity, and require high voltage.

With advancements made at MDL, silicon detectors now have an ultraviolet response five to 10 times higher than image-tube detectors that have flown before. Through nanoengineering, researchers have made it possible to produce silicon arrays with unprecedented capabilities. They have achieved tailorable response such that these silicon detectors have high sensitivity in the ultraviolet while rejecting background from visible and infrared sources. In collaboration with the industry, MDL is leveraging investments in silicon imaging technology to develop and deliver unique ultraviolet sensors based on the latest silicon detector designs.

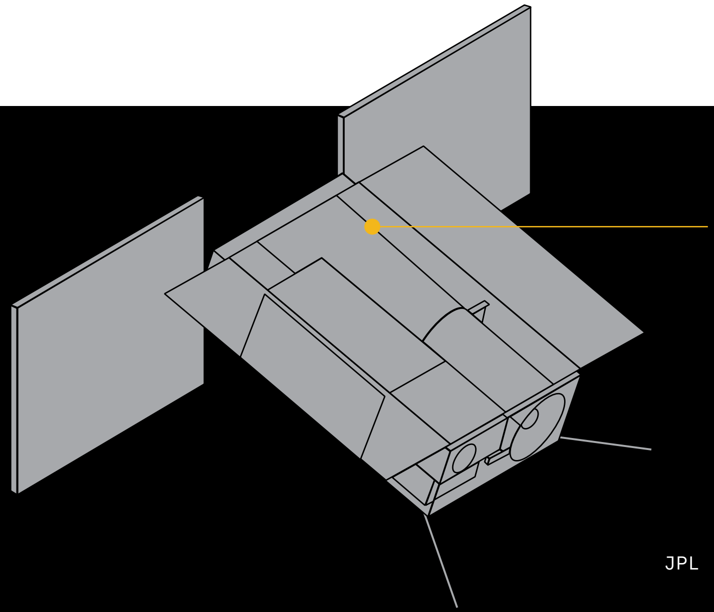
Principal investigator for SPARCS is Professor Evgenya Shkolnik at Arizona State University's School of Earth and Space Exploration. Principal investigator for the detector and camera is Shouleh Nikzad at MDL.



UV FLUX *The stellar UV flux has a dramatic effect on a planet's detected atmospheric content. The plot shows an Earth-like planet spectrum in the habitable zone of an active (red) and inactive (gold) M4 dwarf. The spectrum of Earth around the Sun is shown black for comparison. Adapted from Rugheimer et al.,* The Astrophysical Journal, *vol. 809, issue 1, pp. 57, 2015.*

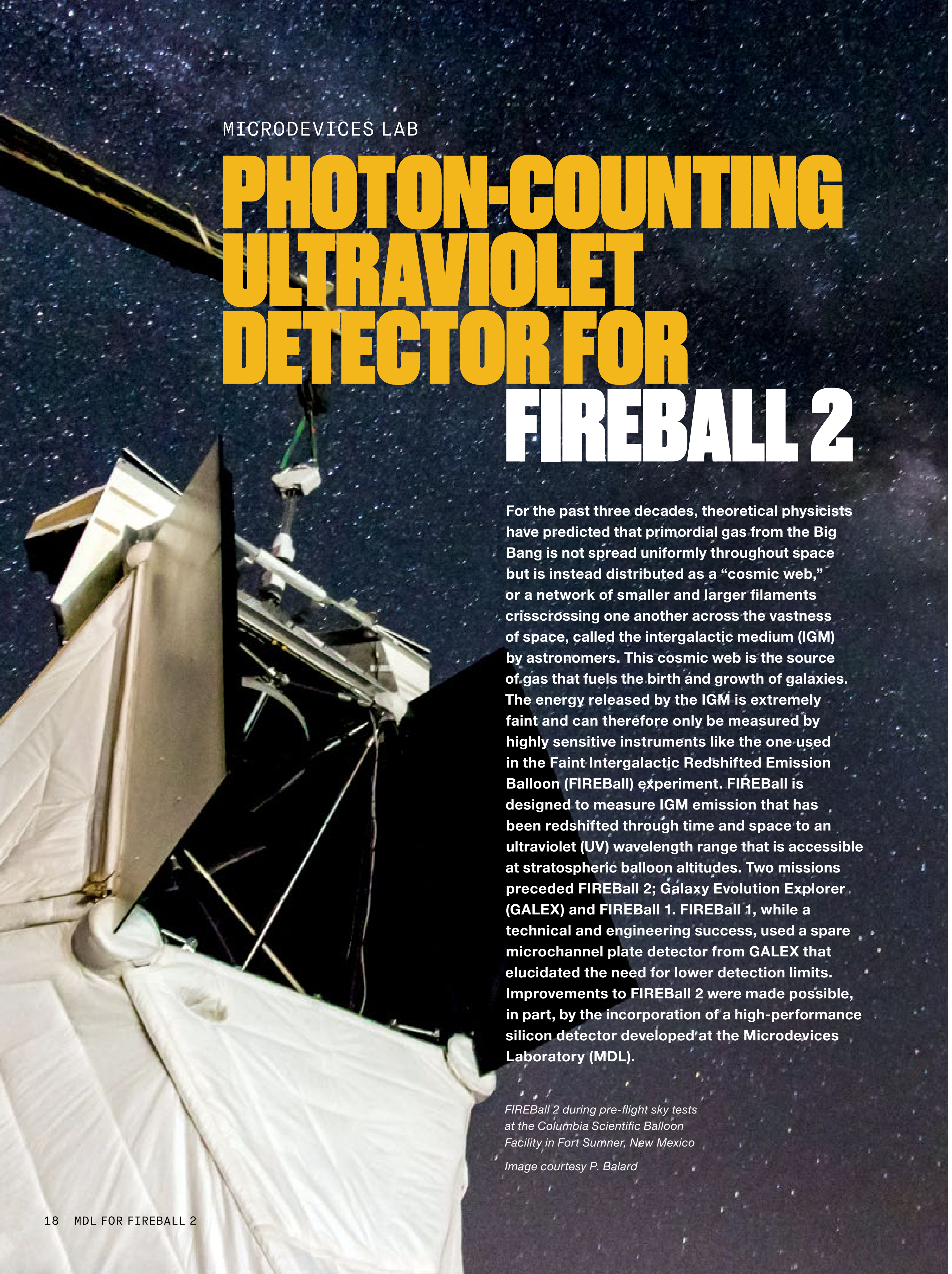


UNINTERRUPTED OBSERVATIONS *The CubeSat platform of SPARCS allows for dedicated, uninterrupted observations of its targets for days or even weeks. Data from such prolonged observations are essential to the development of stellar models but are not available from larger missions such as Hubble Space Telescope (HST) and Galaxy Evolution Explorer (GALEX), which must share observation resources.*



SPARCAM LOCATION

SPARCS is a CubeSat mission that will be built out of six cubical modules, each about 10 centimeters on a side.



MICRODEVICES LAB

PHOTON-COUNTING ULTRAVIOLET DETECTOR FOR FIREBALL 2

For the past three decades, theoretical physicists have predicted that primordial gas from the Big Bang is not spread uniformly throughout space but is instead distributed as a "cosmic web," or a network of smaller and larger filaments crisscrossing one another across the vastness of space, called the intergalactic medium (IGM) by astronomers. This cosmic web is the source of gas that fuels the birth and growth of galaxies. The energy released by the IGM is extremely faint and can therefore only be measured by highly sensitive instruments like the one used in the Faint Intergalactic Redshifted Emission Balloon (FIREBall) experiment. FIREBall is designed to measure IGM emission that has been redshifted through time and space to an ultraviolet (UV) wavelength range that is accessible at stratospheric balloon altitudes. Two missions preceded FIREBall 2; Galaxy Evolution Explorer (GALEX) and FIREBall 1. FIREBall 1, while a technical and engineering success, used a spare microchannel plate detector from GALEX that elucidated the need for lower detection limits. Improvements to FIREBall 2 were made possible, in part, by the incorporation of a high-performance silicon detector developed at the Microdevices Laboratory (MDL).

FIREBall 2 during pre-flight sky tests at the Columbia Scientific Balloon Facility in Fort Sumner, New Mexico

Image courtesy P. Balard

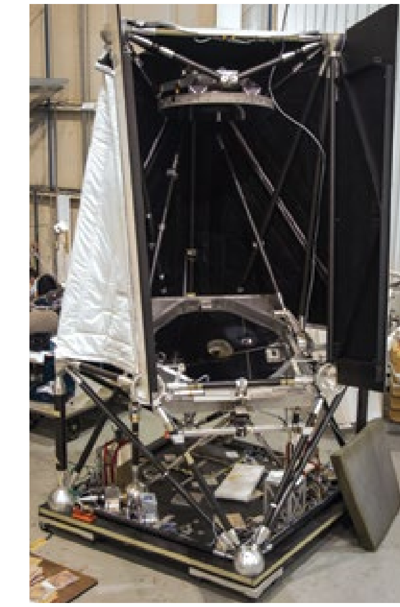
FIREBall 2, a balloon-borne UV spectrograph jointly funded by NASA and France's National Centre for Space Studies, is designed to observe emission from the IGM and the circumgalactic medium, the diffuse gas around galaxies. These emissions carry signatures of galactic feedback, including matter and energy outflows. Understanding the morphology, thermodynamics, chemistry, and kinematics of this gas is key to understanding galaxy formation and evolution.

The new FIREBall instrument is optimized for narrowband observations spanning the stratospheric window (200–210 nanometers) centered at 205 nanometers. These measurements are complementary to those made by Caltech's Cosmic Web Imager, which examines IGM emission at a larger redshift.

Using MDL technologies, JPL has delivered a high-performance, UV, photon-counting science detector by optimizing the response of an electron multiplying charge-coupled device (EMCCD) to the observation window of FIREball 2. The EMCCD is a powerful imaging architecture with photon-counting capability. When combined with JPL's 2D doping and custom antireflection (AR) coatings, the result is a mission-enabling UV detector with unprecedented quantum efficiency and noise characteristics.

Silicon-based solid-state devices have become the chief imaging detectors for many commercial and scientific applications due to their low noise, large dynamic range, and linear light response. MDL-developed delta- and superlattice-doping (2D-doping) techniques yield silicon detectors with reflection-limited response; AR coatings are used to further improve detector response beyond the reflection limit. AR coatings for the UV wavelength range are particularly challenging because most materials will absorb UV light. We have developed AR coatings using UV-transmitting materials and atomic layer deposition which allows us to prepare coatings with a thickness of only a few tens of nanometers. This approach has enabled our technologies to achieve nearly 80 percent quantum efficiency in the FIREBall 2 window.

The FIREBall mission's principal investigator is Christopher Martin, professor of physics at Caltech. Principal investigator for the Photon-counting Ultraviolet Detector is Shouleh Nikzad at MDL.



FLIGHT READY *FIREBall 2 in the hanger at the Columbia Scientific Balloon Facility in Fort Sumner, New Mexico. Image courtesy P. Balard*

SCIENTIFIC BALLOON
Scientific Balloon Flight Facility in Fort Sumner, N.M. Image courtesy HySICS Team/LASP

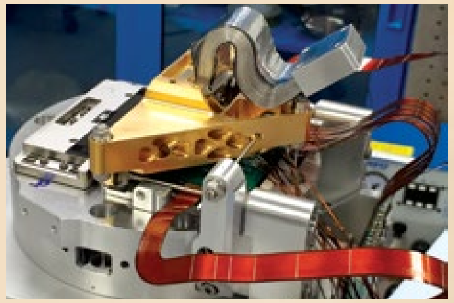
MICRODEVICES LAB

GRATING, SLIT, AND BLACK SILICON FOR EMIT

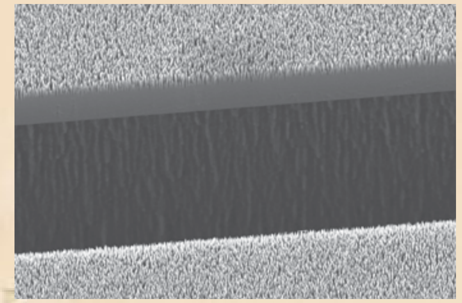
Does mineral dust blown into the atmosphere warm or cool the atmosphere? That is the fundamental question that researchers hope a new, space-based instrument called EMIT (Earth Surface Mineral Dust Source Investigation) will help them answer. Since much of the Earth's desert regions are remote and inhospitable, the best way to study them may be from space. Using imaging spectroscopy methods, EMIT will measure surface soil and mineral composition of the Earth's dust source regions to learn more about its impact on the climate and predict how it can be expected to change in the future. Developed and built at JPL, the imaging spectrometer will benefit from numerous components fabricated in the Microdevices Laboratory (MDL).

In February 2018, NASA selected the JPL-led Earth Surface Mineral Dust Source Investigation (EMIT) as an Earth Venture Instrument for development and deployment to the International Space Station. EMIT will use advanced JPL imaging spectroscopy to measure the mineral composition of the Earth's dust source regions. This will determine the optical and chemical properties of the dust aerosols emitted into the atmosphere during high wind conditions, providing accurate boundary conditions for today's state-of-the-art Earth system models. With accurate initialization, these models will be used to understand the global dust cycle and predict the future role of mineral dust in the Earth's climate system. Mineral dust impacts the atmosphere, oceans, terrestrial ecosystems, cryosphere, and inhabited lands. The EMIT instrument uses a set of technologies invented at JPL for advanced imaging spectrometer instruments and science missions, including: a three-octave, high-uniformity Dyson imaging spectrometer design; submicron adjustable detector mounts; an e-beam fabricated grating; a silicon nitride slit; and a black silicon zero-order light trap. The grating, slit, and light trap are fabricated at MDL. A prototype of the EMIT imaging spectrometer has been developed and used to advance the readiness of these key technologies. High-throughput imaging spectrometers of the EMIT type are relevant to a broad range of future NASA missions to address new science questions on the moon, on Mars, and throughout the solar system.

The principal investigator for the EMIT mission at JPL is MDL's Robert O. Green.



DETECTOR MOUNTS
JPL technology cryogen detector array mount with six degree of freedom adjustment to submicron tolerances



LIGHT TRAP
Black silicon and slit

DUST IN THE WIND
Large dust plume blowing off the Sahara Desert and out over the Mediterranean Sea

Credit: NASA image courtesy Jeff Schmaltz, LANCE MODIS Rapid Response

E-BEAM GRATING
Microdevices Laboratory e-beam fabricated structured blaze concave grating technology for the EMIT prototype imaging spectrometer with atomic force micrograph of achieved structured blaze

MICRODEVICES LAB

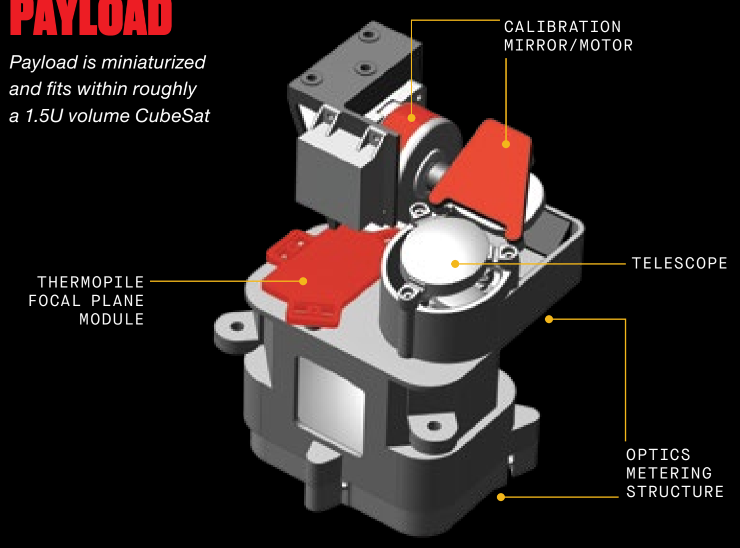
THERMOPILE DETECTOR ARRAY FOR PREFIRE

SEA ICE
2011 composite satellite image shows the expanse of Arctic sea ice and the Greenland Ice Sheet

Credit: NASA

PREFIRE PAYLOAD

Payload is miniaturized and fits within roughly a 1.5U volume CubeSat



As our planet continues to warm, climate scientists need novel ways of exploring the processes that drive change and of measuring the markers that predict such alterations. These scientists recognize that the remote Arctic region of Earth is unique in that it helps regulate the planet's temperature like a thermostat by radiating back into space much of the excess energy from the Sun that is received in the tropics. However, more than half of these Arctic emissions occur at far-infrared (FIR) wavelengths greater than 15 micrometers and have never been systematically measured from space before. A new mission called Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) will use a JPL-designed instrument that uses critical technology from the Microdevices Laboratory (MDL) including a fully custom thermopile detector array. This thermopile array will help probe this little-studied portion of the radiant energy emitted by Earth for the first time, seeking clues about Arctic warming, sea ice loss, and ice-sheet melting. Finally, PREFIRE will explore how changes in thermal infrared emissions at the top of Earth's atmosphere are related to changes in cloud cover and surface conditions below.

In 2018, NASA selected PREFIRE to perform first-of-a-kind infrared and far-infrared measurements of Earth's atmosphere from space. One key question PREFIRE will attempt to answer is: Why is the Arctic warming faster than the rest of the planet?

More than 60 percent of energy radiated from the cold, dry polar regions resides in FIR wavelengths. Energy in these bands is both dynamic and poorly characterized, yet it plays a critical role in defining the rapidly evolving polar climates.

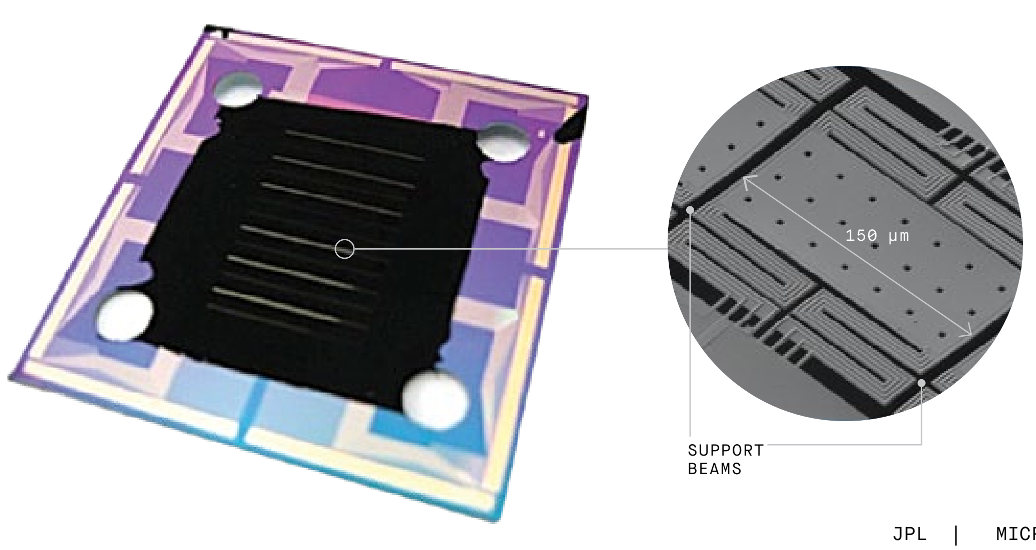
PREFIRE will fly two CubeSat satellites making radiometric measures of the atmosphere between five to 50 micrometers, completely characterizing the variability in FIR emission on scales of hours to months. This spectral data provides critical insight into the surface emissivity, its variability, and the atmospheric greenhouse effect, allowing quantitative modeling of the surface/atmosphere feedbacks that are hypothesized to amplify the effects of climate change. The dual spacecraft measurement capability specifically creates sub-diurnal sampling that can test the hypothesis that time-varying errors in current models of FIR surface emissivity cause biases in estimates of the energy exchange between the surface and the atmosphere of the Arctic. Elucidation and mitigation of these biases through PREFIRE measurements and analyses may reduce the large spreads observed in past projected rates of Arctic warming, sea-ice loss, ice sheet melt, and sea level rise.

CubeSats are lower-cost, lightweight, and very small compared to traditional satellites—some as small as a loaf of bread. Performing accurate and sensitive radiometric measurements across infrared and far-infrared wavelengths in a miniaturized satellite is challenging, but, fortunately, PREFIRE will have the help of MDL's focal plane module (FPM).

In particular, the FPM will use a thermopile detector array designed and fabricated at MDL with a pixel and format size customized for PREFIRE. The array operates uncooled, so minimal resources are needed to integrate the array into each CubeSat. It is important to note that thermopiles are fundamentally insensitive to instrument drift, so it is possible to make accurate radiometric measurements even within a CubeSat where the instrument's thermal environment is not stable.

Each pixel of the thermopile detector array has a broadband optical coating called "gold black" that provides near-unity optical efficiency across the entire spectrum that PREFIRE will measure. Finally, the FPM will utilize custom readout integrated circuits built by Black Forest Engineering that show no measureable low frequency noise. Therefore, the entire FPM can observe the Earth over long integration times to enhance the signal-to-noise ratio of the measurement.

Principal investigator for PREFIRE is Tristan L'Ecuyer, associate professor of atmospheric and oceanic sciences at the University of Wisconsin–Madison. Principal investigator for the Thermopile Detector is Matt Kenyon at MDL.



THERMOPILE DETECTOR CHIP
The FPM utilizes a thermopile detector chip customized for PREFIRE in terms of pixel layout and format size. The chip has "gold black" deposited on the pixels to make the pixels sensitive to infrared and far-infrared light

NEXT

LOOKING BEYOND TOMORROW

At the Microdevices Laboratory (MDL), the future is in our favor. As technology aims to get smaller and smaller, we are already armed with expertise on building micro- and nanoscale devices, giving us a jumpstart on what NASA missions will need in the decades ahead. By investing in highly productive, creative people who seek to answer the most important and curious questions we have in science and technology, MDL has secured a strong track record of thinking outside the box to deliver successful high-risk, high-payoff results. We look forward to an exciting, challenging, and dynamic future of creating new technologies that enable NASA space missions to make unique Earth, planetary, and astrophysics discoveries, and pioneering technology development for many areas of national importance, from medical applications to national security.

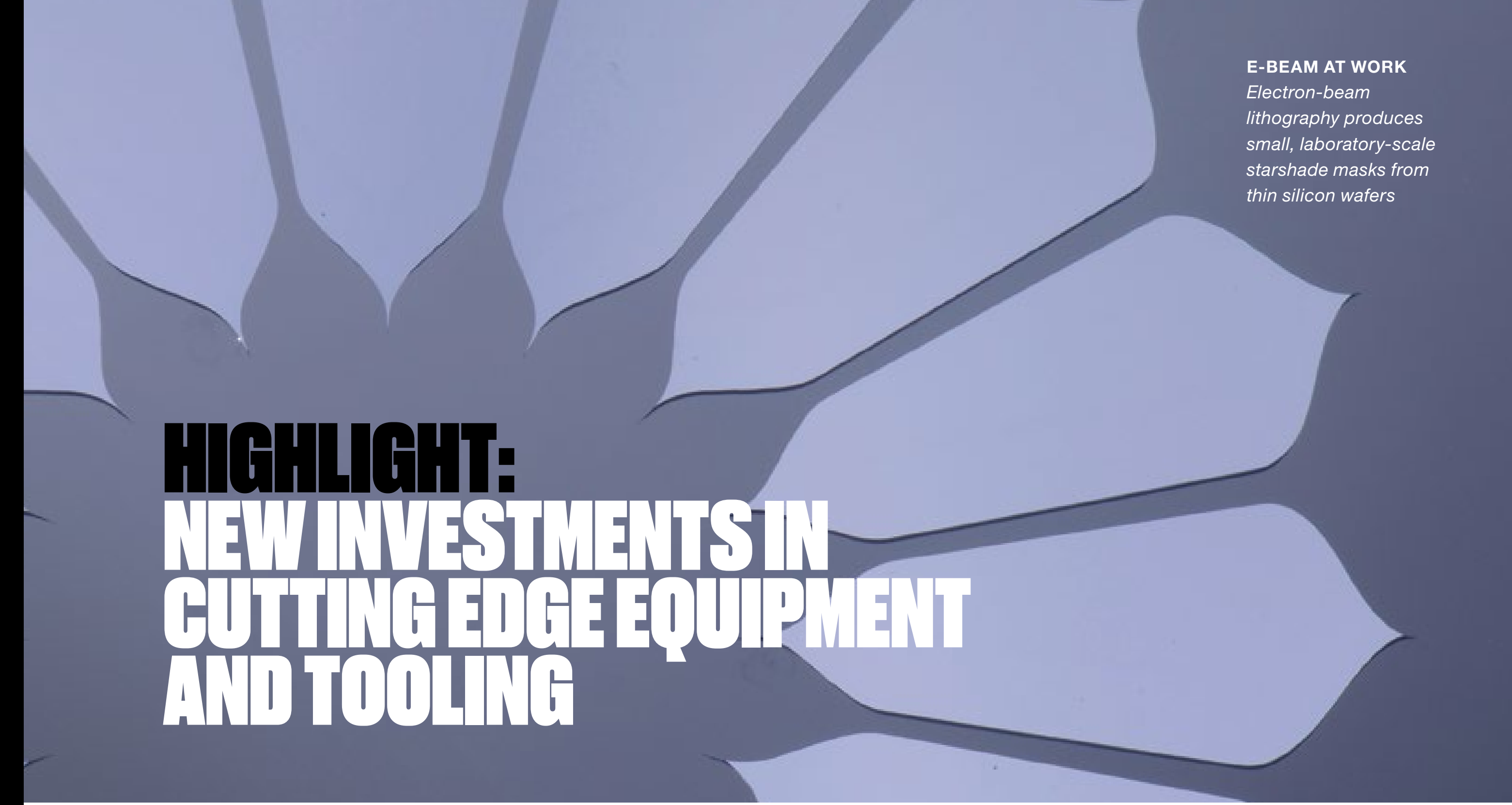
STRATEGIC EQUIPMENT INVESTMENTS

Since its inception, the Microdevices Laboratory (MDL) has delivered a remarkable number of improved sensor technologies and capabilities for JPL and NASA space missions that have enabled enhanced science returns. Sustained strategic investment in a world-class technical staff, critical facility infrastructure, and cutting-edge equipment and tooling are all crucial to achieving and continuing to achieve these important contributions.

The sustained strategic investments over the past 25 years have paid off. Contributions have been and continue to be made through the creation and delivery of improved sensor technologies across a wide swath of the electromagnetic spectrum, from the soft X-ray regime through the ultraviolet, the visible, the near-infrared, the mid-infrared, the far-infrared, sub-millimeter, and millimeter spectral regions.

Highlights of the facility infrastructure include the ability to safely handle and monitor acutely hazardous materials, three separate exhaust systems, certified cleanroom areas down to ISO4 (Class 10), facilities designed and engineered with anti-vibration measures to allow sub-micron processing, and flexible equipment designs and controls allowing the use of different size and thickness wafers and the use of a variety of materials. In addition, a full suite of semiconductor processing equipment providing end-to-end device fabrication are available at MDL. (For complete equipment list, see page 63–64.)

Of course, the improvements to infrastructure and capabilities do not happen without help. The oversight and implementation of numerous infrastructure systems, equipment capabilities, and operations have been maintained, renewed, and upgraded by the members of the Central Processing and MDL Support group assisted by numerous other organizational elements. These elements allow the continuation of the Lab's cutting-edge capabilities and enable its highly educated, talented, and skilled users, researchers, developers, and technologists to continue to contribute now and well into the future.



E-BEAM AT WORK
Electron-beam lithography produces small, laboratory-scale starshade masks from thin silicon wafers

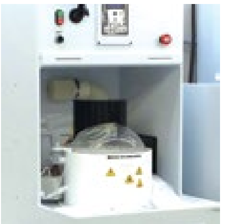
HIGHLIGHT: NEW INVESTMENTS IN CUTTING EDGE EQUIPMENT AND TOOLING

PATTERNING CAPABILITY

The installation, qualification, and the initial direct-write fabrications took place for a state-of-the-art **JEOL JBX 9500FS Electron Beam Lithography System** in 2017. This major investment took two years to procure and fabricate and one year to install and qualify. The dedication ceremony took place on June 7, 2017, when Michael Watkins, director of JPL, initiated the first official patterning write from this system.

ETCHING CAPABILITY

An **Oxford PlasmaPro 100 Cobra Load-Locked Cryo/ALE/Bosch Etcher,** procured and installed in the past year, will allow the flight-qualified fabrication of black silicon—a textured silicon surface that acts as a zero-order-light-trap to provide world-record broadband light-absorption efficiency.

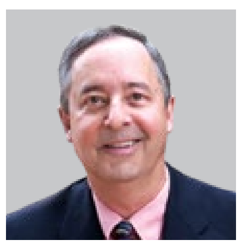


SAMPLE PREPARATION CAPABILITY

The **Laurell Technologies EDC 650 Dilute Dynamic cleaning System (DDS)** is another new equipment investment that improves the processing yield through less contamination during sample preparation. Not only does this capability improve the ability to clean surfaces, it does so with less cleaning material waste since it utilizes activated vapor streams onto a spinning substrate as opposed to large liquid vats.

MDL VISITING COMMITTEE

Meeting every two years to review the ongoing work at the Microdevices Laboratory (MDL) and make valuable suggestions for future directions, the Visiting Committee, consisting of a broad spectrum of highly talented and accomplished individuals, has recognized the leadership, vision, and innovation of MDL. They have acknowledged that MDL is a key national asset with unique state-of-the-art capabilities and staff well-focused on space applications of micro- and nanotechnologies. The committee's reports have been of tremendous value in the pursuit of the highest quality research and development programs targeted toward the key scientific and technical goals of interest to NASA and our other sponsors.



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Committee Chair
Dean of College of Optical Sciences and Professor of Optical Sciences
University Of Arizona

DR. BARBARA WILSON
Committee Co-Chair
Retired Chief Technologist
Jet Propulsion Laboratory

DR. EUSTACE DERENIAK
Former Chairman (2008–2015)
Professor of Optical Sciences, Electrical and Computer Engineering—University of Arizona

DR. SANJAY BANERJEE
Director of Microelectronics Research Center and Professor of Electrical and Computer Engineering
University of Texas at Austin

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University of Maryland, College Park, MD

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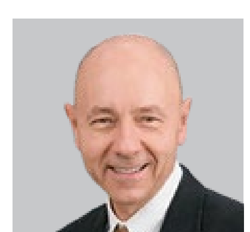
Professor of Electrical and Computer Engineering
Georgia Institute of Technology

MR. GEORGE KOMAR
Associate Director
NASA's Earth Science Technology Office (ESTO)



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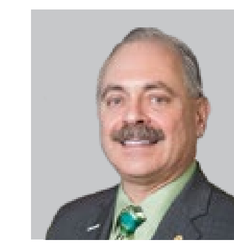
Harvard University

DR. OSKAR PAINTER
Professor of Applied Physics
California Institute of Technology



ALBERT P. PISANO
Professor and Dean of the School of Engineering
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DR. REGINA RAGAN
Professor of Chemical Engineering and Materials Science
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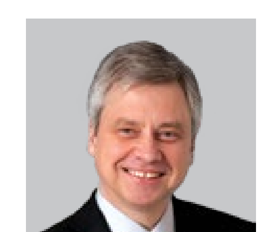
DR. RONALD REAGO
Director of Communications, Electronic Research, Development and Engineering Center (CERDEC)
Night Vision and Electronic Sensors Directorate (NVESD)

MR. DAVID SANDISON
Director of the Center for Microsystems Science, Technology & Components
Sandia National Laboratories

DR. ROBERT WESTERVELT
Professor of Physics and Applied Physics
Harvard University



DR. JONAS ZMUIDZINAS
Former JPL Chief Technologist, former Director of JPL's Microdevices Laboratory, and Merle Kingsley Professor of Physics
California Institute of Technology

DR. MEIMEI TIDROW
Chief Scientist for Focal Plane Arrays at the U.S. Army RDECOM CERDEC
Night Vision and Electronic Sensors Directorate (NVESD)

INNOVATIVE INSTRUMENTS

Building instruments for scientific investigations requires curiosity, dedication, and new ways of looking at old problems. At the Microdevices Laboratory (MDL), we aim for the trifecta of efficient, reliable, and cost-effective in everything that we do, including key devices that we focused on this year: next-generation solid-state magnetometers, highly miniature gas chromatograph mass spectrometers, and multiplexed subcritical water extractors. Having a unique and diverse set of state-of-the-art micro- and nano-fabrication tools located in one place gives MDL the ability to pioneer the development of original devices and novel assembly techniques. And by being at the forefront of the inspiration and implementation of new innovations developed from cutting-edge research at JPL and throughout NASA, MDL-designed technology enables instruments to be greater than the sum of their parts.

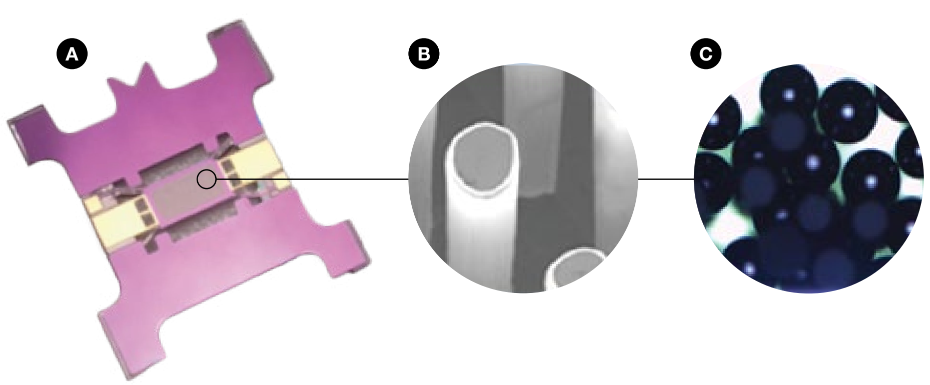
SAM

Next Generation Gas Chromatograph Mass Spectrometers

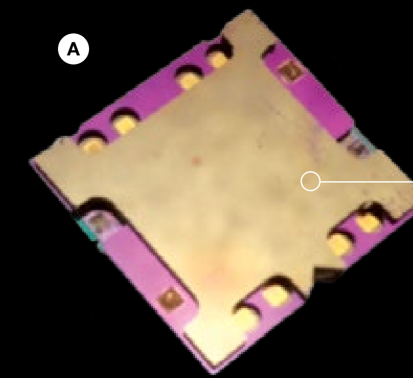
Recent years have witnessed significant progress made in the miniaturization of mass spectrometers for a variety of field applications. The main focus at JPL is on the two most common space-related applications of mass spectrometers: studying the composition of planetary atmospheres and monitoring air quality on manned space missions. JPL's quadrupole ion trap mass spectrometer product has been under development for human space flight applications since 2003 and for planetary applications since 2011. NASA has made a significant commitment to this measurement technology on which astronaut lives depend, and its precision, mass, power, and robustness will benefit both human exploration and planetary science.

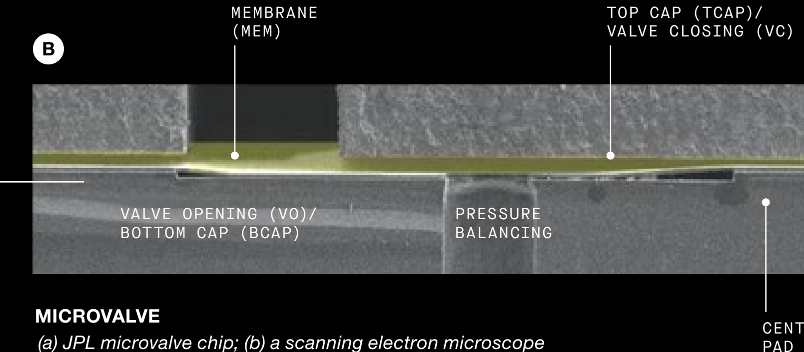
The Microdevices Laboratory (MDL) has been developing a microelectromechanical system (MEMS) gas chromatograph that is a crucial part of JPL's Spacecraft Atmosphere Monitor (SAM). The SAM instrument is a highly miniaturized gas chromatograph/mass spectrometer for monitoring the atmosphere of crewed spacecraft for both trace organic compounds and the major constituents of the cabin air. The SAM instrument, scheduled for launch to the International Space Station (ISS) in 2019, is the next generation of gas chromatograph/mass spectrometer, based on JPL's Vehicle Cabin Air Monitor (VCAM). VCAM was launched to the ISS in April 2010 and successfully operated for two years. SAM consists of the quadrupole ion trap mass spectrometer interfaced with a micro-fabricated preconcentrator and gas chromatograph unit (together forming the PCGC subassembly) and a small gas carrier reservoir. The micro-fabricated PCGC unit employs a novel MEMS PCGC technology that is implemented by combining a MEMS preconcentrator, a microvalve, and gas chromatograph chips that replace the macro PCGC components in the VCAM: This significantly reduces the total volume and mass of the gas chromatograph/mass spectrometer instrument from 64.4 L and 37.9 kg (VCAM) to 10 L and 9.5 kg (SAM).

The JPL preconcentrator consists of the silicon doped heater and a Carboxen layer in the chamber (see below). The heater can be flash heated to 250°C in 0.5 seconds due to the thermally isolated design and material of the heater, which are made possible by through-etching around the heating plate and a silicon insulator, respectively. The JPL preconcentrator demonstrated more than a 10,000-fold concentration increment for alcohols, which is high enough for analysis of parts per billion concentrations of volatile organic compounds.



PRECONCENTRATOR
(a) Thermally isolated silicon heater in the middle chamber where Carboxen adsorbent particles are packed; (b) microposts for attaching micro/nano adsorbents; (c) Carboxen 1000 particles to be packed into the middle chamber that has no micropost



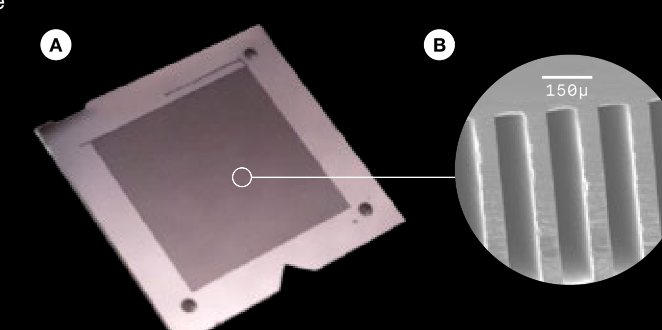


MICROVALVE
(a) JPL microvalve chip; (b) a scanning electron microscope image of the cross-sectional view of the JPL microvalve

The JPL microvalve is an electrostatically operated microvalve that is composed of three main components: the top cap (TCAP)/valve closing (VC), the membrane, and the valve opening (VO)/bottom cap (BCAP) (see above). The VC/TCAP and VO/BCAP are bonded as a stack using gold diffusion bonding technology. The VC/TCAP and VO/BCAP stack sandwich is bonded to the membrane layer using benzocyclobutene adhesive to complete the microvalve assembly. The membrane layer has four membranes embedded, each of which independently moves up and down in response to an applied electric field between the stacks.

These are the first electrostatic MEMS valves to achieve more than a million cycles. In fact, they achieved 47 million cycles before failure, which is equivalent to 5.9 years of operation when the valve is switched every four seconds. Other unique features include the center pad to reduce opening voltage and charge buildup; a pressure balancing mechanism to lower differential pressure across the membrane, lowering stress and allowing the valve to open against high pressure; and an interface treatment to prevent charge buildup, which is the main failure mode of most other electrostatic valves.

The JPL gas chromatograph microcolumn is composed of multiple stacks of a 1 m serpentine column and a capping layer, which are hermetically sealed by metal diffusion or direct fusion bonding. The serpentine channel generates better separation than that of spiral channel design in the micro level of the chip design. Silicon-silicon layers of microcolumn deliver less tailing and peak broadening than conventional silicon-Pyrex microcolumns due to the higher uniform temperature profile. A photograph of the serpentine channel and a cross-sectional scanning electron microscope image of the bonded serpentine channel is below. The gas chromatograph microcolumn also has a uniform self-assembly monolayer coating along the wall of the serpentine channel, which is facilitated by unique coating methodology.



GAS CHROMATOGRAPH MICROCOLUMN
(a) JPL gas chromatograph microcolumn; (b) a scanning electron microscope image of the cross-sectional view of the gas chromatograph serpentine channel

JPL's in situ chemical analyzer team in Chile's Atacama Desert

LAB ON A CHIP

Portable Subcritical Water Extraction Unit and Microchip Electrophoresis Chemical Analyzer

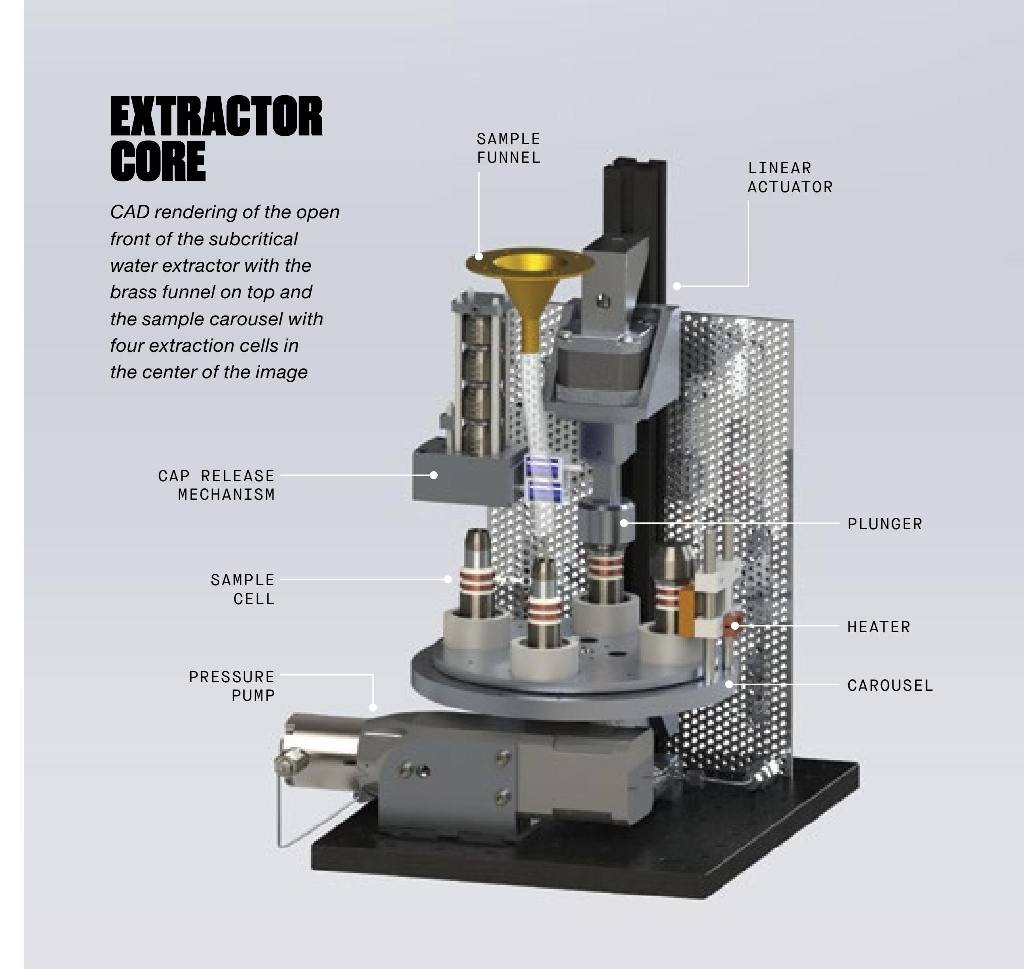
It has been over 40 years since the Viking missions arrived at Mars and became the first landed missions to search for chemical signs of life on another planet. Along with its famous biology experiments, Viking was also equipped to scan for the presence of organic molecules using gas chromatography-mass spectrometry. The results of the scan showed the presence of only carbon dioxide and water, nothing that astrobiologists could use to indicate the presence of life on Mars. However, it is possible that organic material could be locked within selected minerals on the Martian surface and Viking just did not have the instrumentation to access it. By incorporating an extraction step prior to in situ organic analysis, in addition to new surface sampling methods, it is now possible to release trace-level biomarkers from the sample matrix, or to liberate organics from macromolecular carbon such as proteins or even cells.

To improve the ability of in situ instruments to detect organics in a variety of low-biomass samples, we developed an automated, remotely controlled and multiplexed subcritical water extractor (SCWE) system. The extraction principle is based on the ability of water to change its dielectric constant as a function of temperature and pressure. This enables efficient extraction of both polar and nonpolar, organic and inorganic compounds using a single nontoxic and environmentally benign solvent: water.

The SCWE system receives approximately 2 cm^3 of the drill tailings through its vibrating inlet funnel into one of four extraction cells in the instrument's sample carousel. First, the cell is hermetically sealed; then the cell is filled and precisely pressurized with water; and finally the cell is heated up to the desired temperature, which can be set depending on the target molecules to be extracted. After a defined amount of time, the extract is released from the cell and pumped into an internal collection vessel. Miniaturized electrochemical sensors measure the extract's pH, redox potential, and conductivity, which are important parameters to understand the local habitability and sample characterization prior to down-stream measurements. Afterward, miniaturized valves and pumps automatically portion and transfer the pre-characterized extract to a liquid analyzer such as the Chemical Laptop.

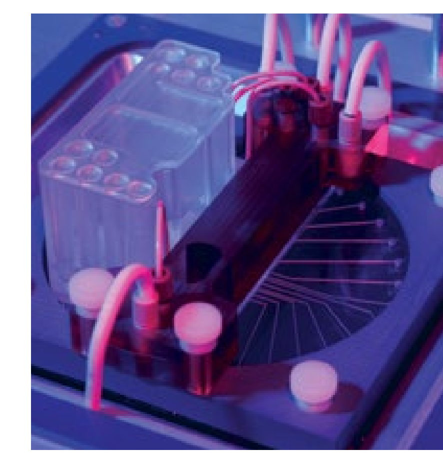
The Chemical Laptop is a portable battery-powered, automated, and reprogrammable microchip electrophoresis instrument coupled to laser-induced fluorescence detection (ME-LIF). It utilizes commercially available microchips, a monolithic pneumatic manifold, and 3D printed chemical cartridges that can hold all the liquids and reagents needed for ME-LIF analysis of amino acids or carboxylic acids. Using this base hardware, the user is able to "reprogram" the system to perform a variety of different chemical analyses.

Earlier this year, the SCWE prototype was taken to the Atacama Desert in Chile as part of the Atacama Rover Astrobiology Drilling Studies effort, a multi NASA-center, Planetary Science and Technology through Analog Research (PSTAR) project led by Ames Research Center. In the field, the extractor unit was installed on Ames's autonomous test rover platform KREX-2 and tested. The entire process was performed automatically by an onboard ARM Cortex-M4 processor that reads from each sensor, controls the various actuators, and communicates with the operator's computer. Remote operations were performed by connecting the Ethernet port of the extractor to a TCP/IP network to send commands and display measurement data on a web server. To our knowledge, this was the first time an automated and remotely controlled subcritical water extraction, or "dirt-to-data" process, has been performed in the Atacama Desert. To get further organic compositional data about the dirt, the extracts from the field were collected and returned to JPL for analysis by the Chemical Laptop.



EXTRACTOR CORE

CAD rendering of the open front of the subcritical water extractor with the brass funnel on top and the sample carousel with four extraction cells in the center of the image



CHEMICAL LAPTOP

A closeup of the liquid handling stage on the microchip electrophoresis chemical analyzer (Chemical Laptop)

MAGNETOMETER

Planetary Magnetic Field Sensing with Quantum Centers in Silicon Carbide

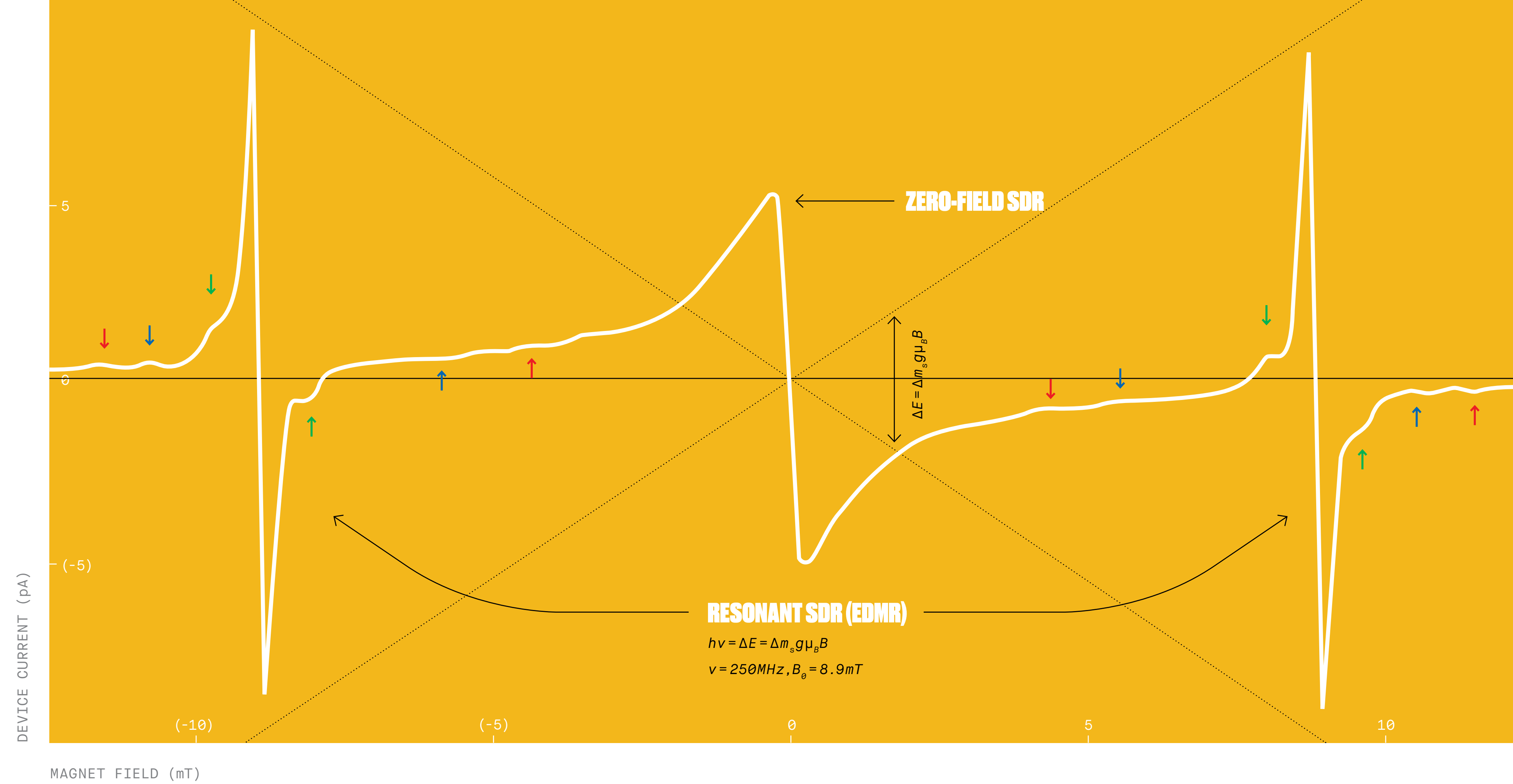
In the Microdevices Laboratory (MDL), researchers are working to develop a next-generation solid-state magnetometer that leverages quantum centers—i.e. atomic scale defects—intrinsic to a silicon carbide (SiC) semiconductor to sense the magnetic fields of planetary bodies. These mid-gap quantum centers give rise to a magnetoresistive response that is facilitated by electron-nuclear hyperfine mixing of the electron spin pairs involved in spin-dependent recombination (SDR) at near-zero magnetic fields. The zero-field SDR phenomenon therefore allows for the electrical readout of a spin-dependent current that encodes the ambient magnetic field in which the sensor is immersed. It is the first ever magnetometer of its kind.

Magnetometers are essential for scientific exploration of planetary bodies, as they can remotely probe the interiors of planets to gain insight on internal composition, dynamics, and even the evolution of the body being investigated. These instruments are therefore ubiquitous on almost all missions in space. If shown to be as sensitive as optically pumped atomic gas and fluxgate magnetometers, the SiC Magnetometer (SiCMag) being developed in MDL could be the future instrument of choice since it is significantly less complex and smaller than previous designs. As a result, SiCMag is well-suited for implementation on nano- or pico-satellites where swarms or a constellation of very small research spacecraft can be deployed for science returns not possible with a single large-scale spacecraft. Additionally, because of SiCMag's simplicity and small scale, dozens can be placed around a large-scale spacecraft which allows for inter-sensor calibration, redundancy, gradiometric measurements, and cancellation of the contaminant spacecraft field, which could potentially remove the need for a magnetometer boom.

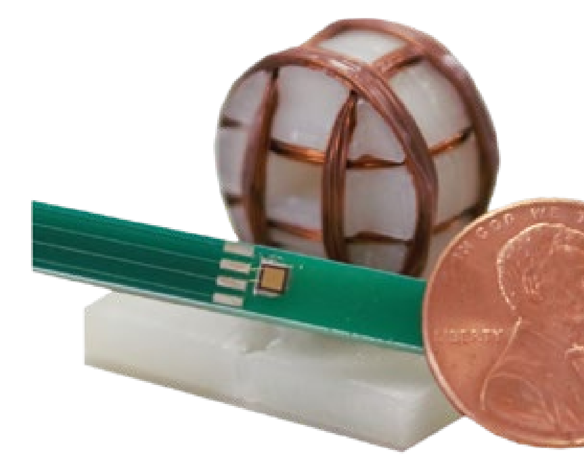
In essence, the entire instrument is composed of a SiC diode enclosed by three very small sets of orthogonal Helmholtz coils, a high-gain current amplifier, a few analog-to-digital and digital-to-analog converters, and a field-programmable gate array (FPGA). The coil system is used to modulate the ambient magnetic field in each dimension with a different frequency that is sensed by the diode. The current from the diode is amplified, conditioned, and then sampled prior to being digitally demodulated in the FPGA for extraction of the three frequency-division multiplexed vectorized current components. A controller within the FPGA tracks the zero-crossing of each component, which is proportional to the ambient magnetic field in each axis and therefore used to null the field at the sensor using the three-axis coil system. Note that no optical or high frequency radio components are required for the instrument.

SiCMag inherits many of its important features from the 4H SiC crystalline sensor that lies at the heart of the instrument. SiC is extremely robust and has the ability to operate in harsh environments due to the wide bandgap (3.3 electron volts) of the material. It therefore has the potential to operate in the high-radiation belts of Jupiter or even on the hot Venusian surface, which can exceed 460 degrees Celsius. This robustness provides SiCMag with the ability to simultaneously be used as a total dose radiation monitor as well as a temperature sensor. Additionally, the magnetic isotopes of the host and dopant atoms that are responsible for the nuclear hyperfine interaction act as tiny bar magnets in the vicinity of the quantum center site. These magnetic signatures allow for the magnetometer to self-calibrate and do not change with time or temperature, as they are fundamental physical constants in nature.

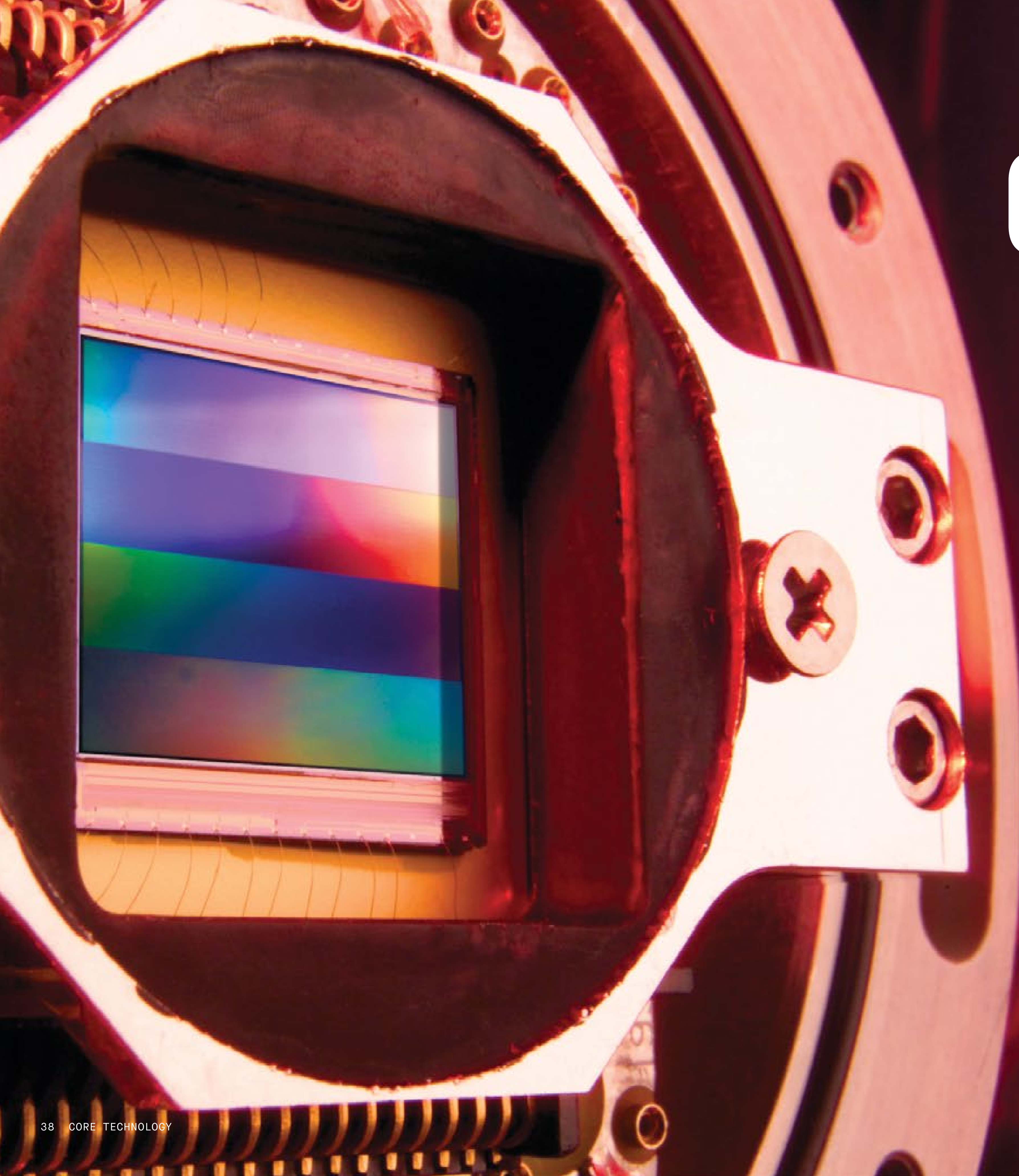
Currently, our "off-the-shelf" sensor is characterized with a sensitivity on the order of 100 $nT/Hz^{1/2}$, as it was not designed in any way for magnetometry. We are currently working with NASA's Glenn Research Center to design and fabricate a variety of custom sensors, which we foresee will operate with a sensitivity on the order of 1 $nT/Hz^{1/2}$ with the aid of quantum center engineering via controlled proton irradiation. SiCMag is not currently set to fly on a mission due to the technology's infancy, but there has been a lot of interest in flying the instrument on a CubeSat or even a drone here on Earth.



▲ **DEFECT SPECTRUM**
Low-field defect spectrum of a 4H SiC diode, implanted with nitrogen, illustrating the resonant spin-dependent recombination (electrically detected magnetic resonance at n = 250MHz) and zero-field spin-dependent recombination (hyperfine mixing). The arrows illustrate the electron-nuclear hyperfine interactions that allow for self-calibration and facilitate the mixing of the quantum center energy states.



SiC SENSOR
Photograph of the SiC sensor and the three-axis, 3D printed Helmholtz coil system used to modulate and null the external magnetic field



CORE TECHNOLOGY

The Microdevices Laboratory's (MDL) leadership, vision, and innovation is illuminated in its rise to the challenge of JPL and NASA missions through its contributions of core technologies. As JPL pursues some of NASA's most ambitious scientific and technical quests, technological advances achieved at MDL serve critical micro- and nanotechnology needs for finding answers and for devising pathways for new explorations. By fostering a community in which one can interact with people with different backgrounds, interests, and expertise, unexpected inspirations become a way of life. JPL excels at bringing experts together to create an environment where new ideas can evolve into useful technologies, and MDL exemplifies this spirit of collaboration. From infrared photodetectors and focal plane arrays to semiconductor lasers and unique fabrication techniques, the MDL team works together to help position JPL at the cutting-edge of core space and planetary mission technology.

DIFFRACTIVE OPTICS

Electron Beam Generated Diffractive Optics Components

The Microdevices Laboratory (MDL) develops electron beam lithography techniques to fabricate unique nano-structures and optics with the aim of pushing the state of the art even further and establishing breakthrough technologies that can enable entirely new instrument and observatory architectures.

A variety of JPL flight and research projects rely on MDL's capability to fabricate special-purpose components for both NASA and non-NASA instruments. Lab members have developed nano-patterning processes for fabricating both binary-layered and grayscale surface-relief structures in a variety of polymers, dielectrics, metals, and substrate materials. This allows the creation of nearly arbitrary transmissive and reflective diffractive optics, such as blazed gratings, lenses, and computer-generated holograms, for wavelengths ranging from ultraviolet to long-wave infrared. Further, we have developed custom E-beam calibration techniques, substrate-mounting fixtures, and pattern preparation software to allow fabrication of these diffractive optics on non-flat (convex or concave) substrates with up to 10 millimeters of height variation. This has enabled the fabrication of high-performance convex and concave diffraction gratings for Offner- and Dyson-type imaging spectrometers that have been used for many airborne and spaceborne instruments.

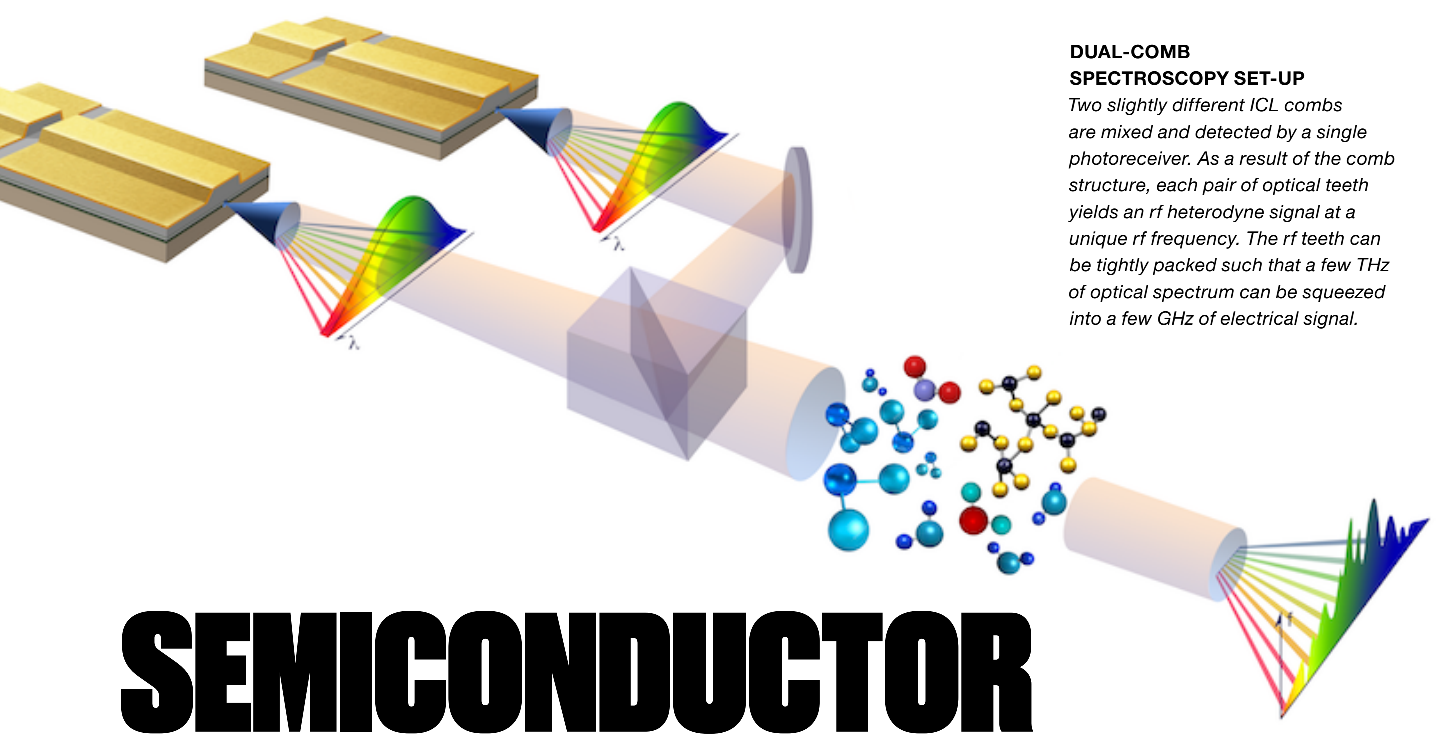
PATTERNING CAPABILITY

The JEOL JBX 9500FS Electron Beam Lithography System investment provides improved capabilities with a 3.6 nanometer spot size, 100 kV and 48 kV operation modes, and two times more resolution and four times the speed of the previous 17-year-old system that it replaced. This provides MDL an opportunity to continue its leadership in fabricating diffractive optic gratings on curved surfaces, with up to 10 millimeters of curvature on substrates up to nine inches in diameter. This capability, together with processes developed in MDL over the past 26 years to provide analog relief surface profiles have enabled the fabrication of the game-changing Offner- and Dyson-type imaging spectrometers. These spectrometers are transformational in that they allow the miniaturization of spectrometers from the size of a small table to the size of a pound cake or a soda can with improved performance and sensitivity over an extended wavelength regime. The system also allows the fabrication of coronagraph occulting masks to mask the light from stars to allow the direct imaging of exoplanets. Other supporting applications are: the fabrication of precision Bragg spectral gratings to eliminate the side lobes of semiconductor lasers to obtain pure single-mode light sources for absorption spectroscopy, precision nanoscale patterning for quantum capacitance detectors and plasmonic devices, and 3D patterning to create shaped pillars with channels that allow capillary metal pumping for micro-electrospray propulsion concepts. The current list of space missions with deliverables from this electron-beam lithography direct writing capability includes:

- Wide Field Infrared Survey Telescope (WFIRST) coronagraph instrument, supporting both the hybrid Lyot coronagraph (HLC) and shaped-pupil coronagraph (SPC) designs
- Mars 2020's Planetary Instrument for X-ray Lithochemistry (PIXL) instrument gratings
- Mars 2020's Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument gratings
- Europa's Mapping Imaging Spectrometer for Europa (MISE) gratings
- Gratings for EMIT, the Earth Surface Mineral Dust Source Investigation mission

E-BEAM DEDICATION CEREMONY
On June 7, 2017, JPL Director Mike Watkins initiated the first official patterning write from this system

E-BEAM LITHOGRAPHY
State-of-the-art JEOL JBX 9500FS Electron Beam Lithography System at MDL



DUAL-COMB SPECTROSCOPY SET-UP
Two slightly different ICL combs are mixed and detected by a single photoreceiver. As a result of the comb structure, each pair of optical teeth yields an rf heterodyne signal at a unique rf frequency. The rf teeth can be tightly packed such that a few THz of optical spectrum can be squeezed into a few GHz of electrical signal.

SEMICONDUCTOR LASERS

The impact of semiconductor lasers in space flight missions has increased steadily with applications in spectroscopy, laser altimeters, metrology, optical communications, and future life-detection fluorescence experiments. In the area of spectroscopy, momentum has built on the success of the Tunable Laser Spectrometer (TLS) instrument on the Mars Science Laboratory (MSL) Curiosity rover. By selectively targeting absorption lines of key atmospheric gases and their less abundant isotopologues across the infrared spectrum, instruments based on TLS technology can provide valuable information about the composition and origins of bodies throughout the solar system. At the Microdevices Laboratory (MDL), significant progress has been made toward developing flight-ready semiconductor lasers operating with low input power across the infrared spectral region from 2 to 10 µm. These lasers are the enabling technology for the next generation of miniature, low-power laser spectrometers for planetary, earth atmosphere, and environmental monitoring on human space missions.

A major challenge for space applications is the reliability of semiconductor lasers. During the past year, our efforts confirmed the reliability of infrared semiconductor lasers in relevant space environments. Lasers packaged in specially designed enclosures were subjected to thermal cycling, random vibration, and shock, and tested for longevity. Based on this study, MDL is now capable of delivering lasers suited for future missions to explore the atmospheres of Venus, Saturn, and other solar system bodies.

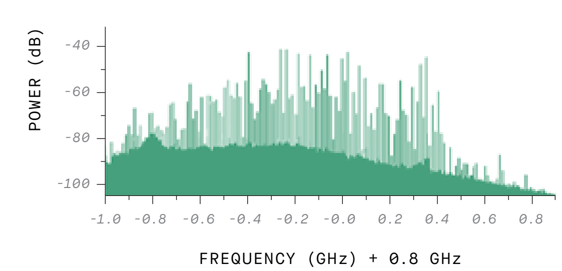
HIGHLIGHT

Dual-comb Gas Spectroscopy with Interband Cascade Laser Frequency Combs

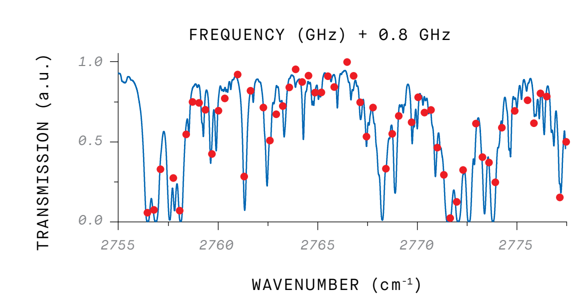
Modern spectroscopic systems can accurately measure the real-time dynamics of mixed atomic and molecular species with weak spectral features, assuming the availability of a broadband source in the relevant wavelength band with high spectral resolution and fast acquisition time. Dual-comb spectroscopy (DCS) offers an unprecedented opportunity to simultaneously acquire broadband and high-resolution spectra within microseconds and is characterized by high signal-to-noise ratio, a small footprint, and implementation free of moving parts. In this technique, shown left, two combs with slightly different repetition rates are interfered on a photodiode generating a radio frequency (RF) comb composed of distinguishable heterodyne beats between pairs of optical comb teeth. This RF comb is easily accessible with RF electronics and contains the relevant spectral information in the optical comb spectra. To perform spectroscopy, a sample is introduced into one or both optical beam paths. The sample's response is encoded on the comb light; this response is then recovered through heterodyne detection. Furthermore, DCS allows using both amplitude and phase information. The latter feature is of great importance in turbulent and noisy environments.

Recently, MDL, in collaboration with the U.S. Naval Research Laboratory, demonstrated the first electrically pumped interband cascade laser (ICL) optical frequency combs. This demonstration has filled the spectral gap around 3–4 µm previously dominated by optically pumped combs with larger complexity and unsuitability for scarce power applications, and it has allowed us to extend these powerful spectroscopic techniques into a spectral region of electromagnetic spectrum where a large fraction of the absorption features associated with carbon-hydrogen bonds are clustered. In contrast to the well-established single-mode distributed feedback lasers (DFB) that probe a small fraction of the optical spectrum at a time, the ICL combs are equivalent to an array of phase-locked DFB lasers that probe multiple spectral regions concurrently with higher precision and sensitivity. The ICL combs allow for broadband and high resolution (<1 MHz) sensing within the same acquisition, utilizing both amplitude and phase information.

Precise control of the ICL comb lasers' parameters, enabled by microfabrication techniques used in the processing of these devices, has allowed us to achieve combs with a slight mismatch in repetition frequency (<0.1% of the center frequency). Therefore, we have been able to map > THz of optical bandwidth into > 600 MHz of electrical spectrum, as shown below. We have used these comb lasers to detect and analyze methane gas in a multi-pass cell configuration. The spectroscopic measurement below shows a one-millisecond acquisition and fit for a 76-meter multi-pass cell with pure methane at atmospheric pressure. The measurement sensitivity demonstrated here (~ ppm) can be further improved (sub-ppm) by tuning the ICL comb emission wavelength to the absorption peak of methane gas (3060 cm^{-1}).



OPTICAL BANDWIDTH
Multi-heterodyne spectrum extracted from a beating signal acquired over 1 ms



SPECTROSCOPIC MEASUREMENT
Spectroscopic measurement (scattered red dots) and fit (solid curve) for a 76 m multi-pass cell with pure methane at atmospheric pressure

UV-VISIBLE DETECTORS

Exciting new science in ultraviolet (UV) astrophysics, planetary science, and helio-physics—beyond discoveries of Hubble Space Telescope, Galaxy Evolution Explorer, and Cassini—can be enabled by employing high-performance detectors, coatings and other instrument technologies.

The Microdevices Laboratory (MDL) has taken a comprehensive approach to improve ultraviolet instrument technologies and instruments for short- and long-term missions. These include development of silicon-based image sensors with spectral tailorability, gallium nitride–based photo-emissive devices for harsh environment applications, stable and high-reflectivity mirror coatings, filters with precise spectral response, combined in compact cameras and imaging spectrometers.

HIGHLIGHTS

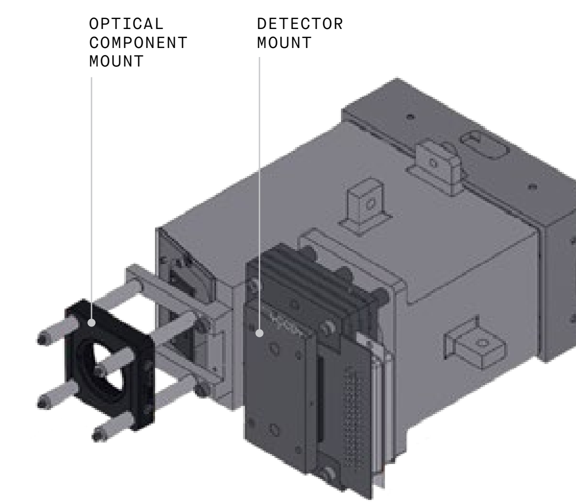
Silicon Molecular Beam Epitaxy System Upgrades
We have upgraded our large capacity molecular beam epitaxy (MBE) to enable new capabilities and reduce downtime by installing a custom-built electron beam silicon source that extends the lifetime of the source material and allows for longer growth campaigns. The hearth—the location of the source material—is approximately four times larger than the previous source, and it can be rotated to expose “fresh” silicon. We are developing n-type superlattice doping using antimony (Sb) and employing a new valved cracker cell. The cell has three-zone heating control; Sb_4 molecules evaporated from bulk source material move through regions of increasing temperature where they are “cracked” to smaller species (Sb_2 and Sb atoms). The result is better incorporation and activation of Sb—a notoriously difficult dopant for silicon due to the bulkiness of Sb_4 and its tendency to segregate. A newly installed ***Auger probe system*** will be used to monitor the growth process in real time providing immediate feedback related to dopant and silicon concentration at the growth surface.

High Reflectivity Mirror Coatings for Future UV/Vis/IR Missions
We have recently developed several new atomic layer deposition (ALD) processes for metal fluorides. The simplicity of this new ALD chemistry enables processing temperatures as low as 100 °C with reduced impurity concentration and superior UV optical properties. MgF_2, AlF_3, and LiF protective coatings were successfully deposited on on Al mirrors for the first time with ALD. We have also demonstrated new low temperature atomic layer etching (ALE) processes that enables the removal of efficiency-killing oxidation from the aluminum surface prior to encapsulation with protective coatings.

High Efficiency Solar Blind Photocathode and Detectors based on Group III-Nitride
Together with SUNY Polytechnic and TU-Delft, we are developing gallium nitride, aluminum nitride, and their alloys for UV detector applications. These wide bandgap III-N materials are intrinsically blind to long-wavelength light; their bandgaps range from 3.4 eV to 6.2 eV, with long-wavelength cut-offs spanning 365–200 nm. We are pursuing technologies for UV photon-counting using III-N photocathodes (PCs) and III-N avalanche photodiodes (APDs). PCs based on III-N materials, typically require cesiation of the surface, which cannot be exposed to air. We are developing band structure engineering techniques that do not require cesiation for activation. Record high quantum efficiencies (QEs) have been achieved, and modeling indicates a path to QE > 50% using achievable material doping and growth.

ULTRAVIOLET IMAGING SPECTROMETER

This year, we extended our development of a miniaturized ultraviolet imaging spectrometer (UVIS) to include a far-ultraviolet (FUV; 100–250 nm) channel. Additionally, we adapted the near-ultraviolet (NUV; 250–600 nm) channel’s configuration to facilitate testing and a pathway towards a flight-like configuration. Testing of the combined NUV and FUV system has yielded promising results. The two spectrometers operate as expected within their spectral ranges and characterization of the system is ongoing.



ULTRAVIOLET SPECTROMETER
Newly designed spectrometer for far-ultraviolet measurements, including an improved detector mount (center foreground) to maintain detector alignment and reduce thermal losses, an optical component mount (left) to permit better integration into test chambers for characterization, and optimized internal construction (not visible) reducing light obstructions and permitting easier replacement of the diffraction grating.

DETECTOR ARRAY
A scanning electron microscope (SEM) image of a part of a detector array. Indium bumps have been deposited on the individual delineated detector pixels to facilitate hybridization with silicon readout integrated circuit (ROIC) for imaging focal plane array (FPA) fabrication.

III-V INFRARED DETECTORS

The Microdevices Laboratory (MDL) has been working to develop a new generation of high-performance, cost-effective infrared photodetectors and focal plane arrays with the flexibility to meet a variety of application requirements. Mercury cadmium telluride, also known as HgCdTe or MCT, is the most successful high-performance infrared detector material to date, offering continuous adjustability in cutoff wavelengths (the longest wavelength of electromagnetic radiation that can be detected effectively) ranging from the short-wavelength infrared (SWIR) to the very long wavelength infrared (VLWIR), making it suitable for a wide range of applications. The challenges associated with MCT are that it is soft and brittle, and therefore requires extreme care in growth, fabrication, and storage. As a result, large-format MCT focal plane arrays tend to be very costly. Focal plane arrays based on traditional bulk III-V semiconductors such as indium gallium arsenide (InGaAs) and indium antimonide (InSb) have excelled in operability, spatial uniformity, temporal stability, scalability, producibility, and affordability, but they lack the versatility in cutoff wavelength adjustability.

Our detector technology is based on artificially designed, multi-layer III-V semiconductor structures that exploit quantum effects to provide continuous adjustability in cutoff wavelength, while simultaneously delivering high signal-to-noise ratio and retaining the advantages offered by the robustness of III-V semiconductors. The development of this technology requires constant exploration and experimentation in design, material growth and characterization, and device fabrication and measurement. The well-maintained state-of-the-art facilities in MDL are essential to our success.

MDL's Infrared Photonics Technology Group has been at the forefront of advanced infrared detector technology development and has created many patented novel concepts in the past, including the antimonides type-II superlattice-based, high operating temperature (HOT) barrier infrared detectors (BIRD) for space and terrestrial applications. HOT BIRD is a breakthrough infrared detector technology capable of operating at 150K

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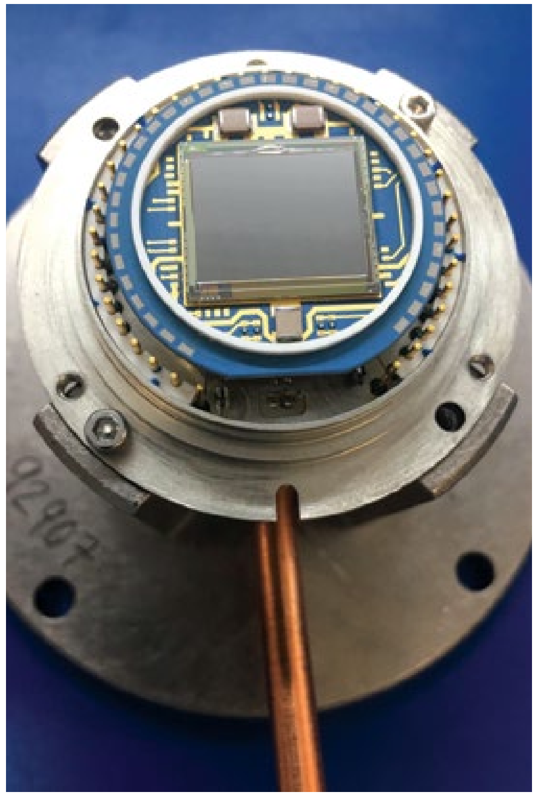
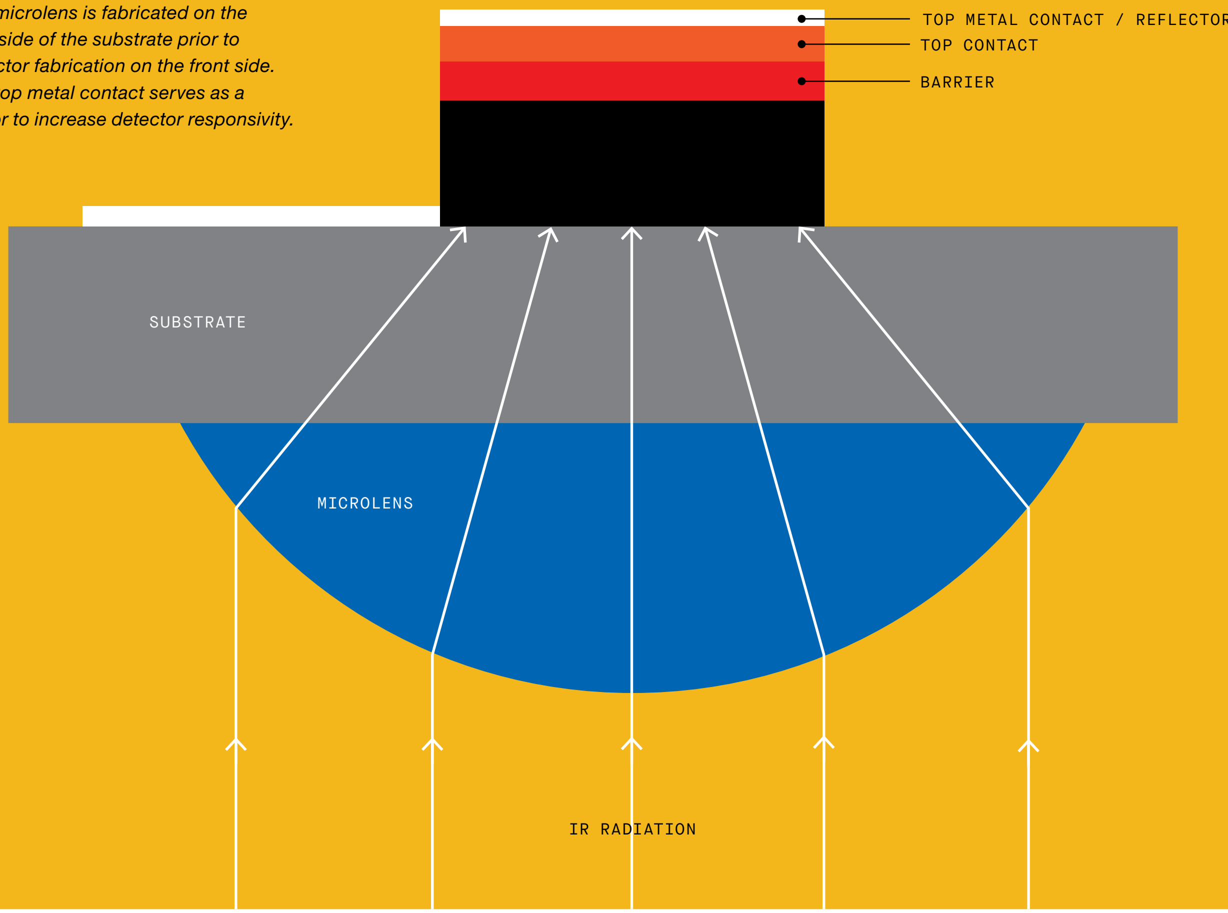


MWIR HOT BIRD
MWIR HOT BIRD focal plane array mounted onto a cold finger of the 6U CubeSat Infrared Atmospheric Sounder (CIRAS)

nBn DETECTOR

Schematic of the nBn detector with a monolithically integrated microlens. The microlens is fabricated on the backside of the substrate prior to detector fabrication on the front side. The top metal contact serves as a mirror to increase detector responsivity.



with spectral coverage of not only the entire mid-wavelength infrared (MWIR) atmospheric transmission window (3–5 µm), but also the SWIR, 1.4–3 µm, and the near infrared (NIR, 0.75–1.4 µm). HOT BIRD focal plane array is at the heart of the Hyperspectral Thermal Imager (HyTI) 6U CubeSat that was recently selected by NASA's In-Space Validation of Earth Science Technologies (InVEST) program.

HIGHLIGHT

High Operating Temperature nbn Detector with Monolithically Integrated Microlens

The sensitivity and operating temperature of infrared detectors can be increased by integrating detectors with optical concentrators such as refractive microlenses. Single microlens and microlens arrays operating in the visible and near-infrared spectral bands are well-developed and are utilized in many devices such as smartphone cameras. However, microlens technology in the mid- and long-wavelength infrared spectral bands lags behind. These spectral bands are important for identification of material composition of planetary surfaces and atmospheres. Therefore, there is a great interest at JPL and at NASA to improve performance of infrared imagers, in particular to increase their operating temperature. Highly sensitive infrared imagers operating at temperatures accessible with thermoelectric coolers are essential for new generation of compact instruments for small satellites.

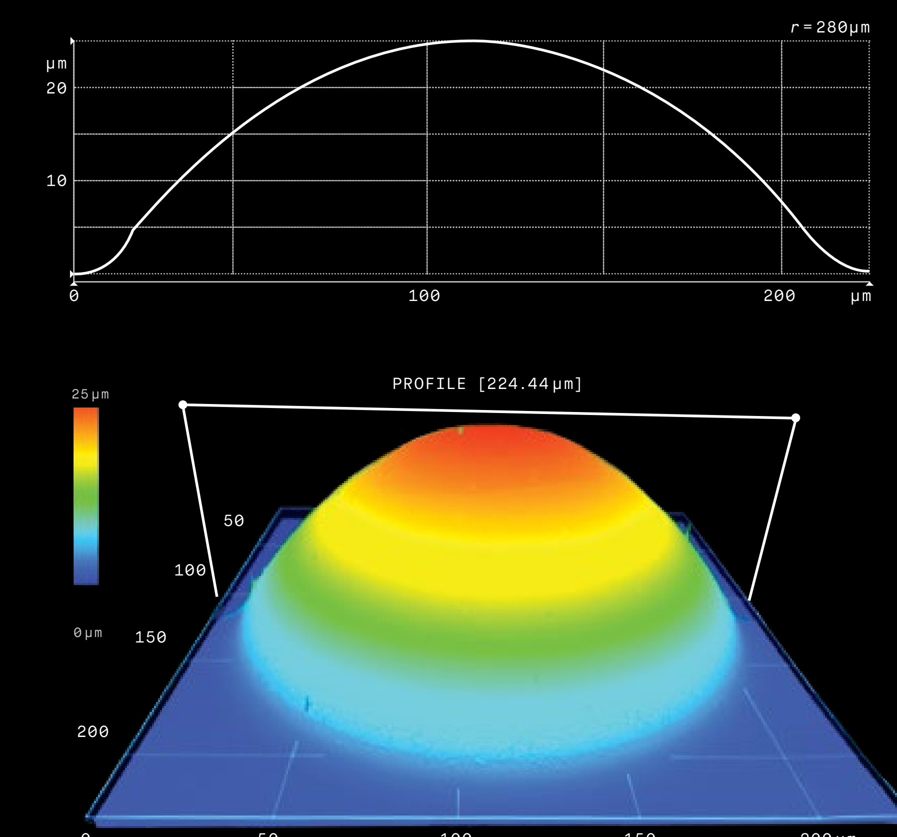
Recently, novel nBn detector architecture, using an n-type absorption layer, an electron Barrier layer, and an n-type contact layer, has been demonstrated. In nBn detectors, a unipolar barrier suppresses the dark current (noise) without impeding the flow of the photocurrent (signal). The increased signal-to-noise ratio leads to higher sensitivity and operating temperature than in the conventional p-n junction photodiode. In recent work, we further increased sensitivity and operating temperature of nBn detectors by monolithically integrating them with microlenses. These microlenses were fabricated on the backside of the detector wafer. The microlens shape sets the focal length, which has to be close to the wafer thickness to optimize light-focusing efficiency. Microlenses are defined by photoresist reflow and material etching processes that were optimized to achieve the desired microlens shape and focal length. After fabrication of the microlens, the detector's pixels were fabricated on the front side. Detectors and microlenses were precisely aligned to each other during fabrication. This method negates the time-consuming optical post-alignments of other microlens-detector integration approaches.

The increase in the optical collection area in the detector with an integrated microlens resulted in a five-fold enhancement of the responsivity. These 4.5 µm cut-off wavelength antireflection-coated detectors with microlenses exhibited a detectivity of $D^*(\lambda) = 2.7 \times 10^{10}$ cmHz$^{0.5}$/W at T = 250 K, which can be reached easily with a single-stage thermoelectric cooler, or with a passive radiator in a space environment. This represents a 25 K increase in the operating temperature of these devices compared to the uncoated detectors without an integrated microlens.

µLENS SHAPE

(Top) Two-dimensional profile of the µlens taken through the µlens vertex as shown in the bottom figure

(Bottom) Three-dimensional map of the µlens shape measured with a Zygo interferometric microscope



SUPERCONDUCTING MATERIALS

The small energy gap and strong non-linearity of superconducting parameters make these materials uniquely suited for ultrasensitive detectors and electronics

The Microdevices Laboratory (MDL) develops and deploys novel superconducting—and related non-superconducting—sensor technologies for application in areas such as astrophysics, optical communications, quantum computing, and Earth, planetary, and cometary sciences.

Beginning in the early 1980s, cryogenic sensor research at JPL focused on superconductor-insulator-superconductor (SIS) heterodyne mixers for astrophysical applications. In collaboration with Caltech, MDL SIS millimeter- and submillimeter-wave mixer technology was deployed in terrestrial radio telescopes, balloon and airborne observatories, and the Herschel Space Observatory. Current development is aimed at cometary water observations. MDL was also an early leader in developing and deploying Hot Electron Bolometer (HEB) mixers, primarily for frequencies above 1 THz. MDL is also developing Josephson and HEB mixers based on the high-temperature superconductor MgB_2, for frequencies above 1 THz and/or for operation at temperatures up to 20 K.

In parallel with these mixer developments, there has been long-term involvement with direct detectors, such as transition-edge sensors (TES). Increasingly complex focal plane arrays based on superconducting TES have been, and are being, deployed at the South Pole on several generations of radio telescopes, including the Background Imaging of Cosmic Extragalactic Polarization telescopes (BICEP-2 and -3), the Keck Array, and the BICEP Array, to gather cosmic microwave background polarization measurements at millimeter wavelengths. A more recent innovation, and a potential replacement for TES devices, are thermal kinetic inductance detectors (TKIDs). Currently under development is a 250 GHz camera with 20,000 such detectors for a BICEP deployment in 2021. TKIDs are bolometers that use the thermally sensitive kinetic inductance of a superconducting film in a resonator to monitor temperature shifts from changes in loading. These detectors offer multiplexing that is extendible to large arrays. JPL engineers are developing a flexible microwave readout system applicable to all types of kinetic inductance detectors and related sensors. It uses commercial off-the-shelf software-defined radios that generate radio frequency interrogation tones and digitized response from cryogenic cameras. The software radio streams this data by high-speed Ethernet to a desktop computer that demodulates and filters the data, accelerating demanding computations in the computer's graphics card. This system is more flexible than a field-programmable gate array-based solution because it is programmed with conventional languages and is already facilitating the study of novel readout techniques.

Microwave kinetic inductance detectors (MKIDs) originated at Caltech and JPL and are attracting increasing interest due to the promise of larger and more sensitive detector arrays for key astrophysical and planetary science investigations. With support from the Office of Naval Research, an instrument is currently under construction that will house a 2000 pixel MKID dual polarization array (4,000 detectors) for terrestrial passive millimeter-wave imaging in degraded optical environments. Prototype arrays have demonstrated photon noise-limited sensitivity for imaging a 300K background. This instrument will also serve as a technology demonstrator for future astrophysics experiments such as the Stage-4 ground-based cosmic microwave background experiment (CMB-S4).

In collaboration with Professor Ben Mazin's group at UC Santa Barbara, near-infrared-optical MKIDs are also being deployed on the 10,000-pixel Dark-speckle Near-infrared Energy-resolved Superconducting Spectrophotometer (DARKNESS) at Palomar Observatory's 200-inch Hale telescope and on the 20,000 pixel MKID Exoplanet Camera (MEC)

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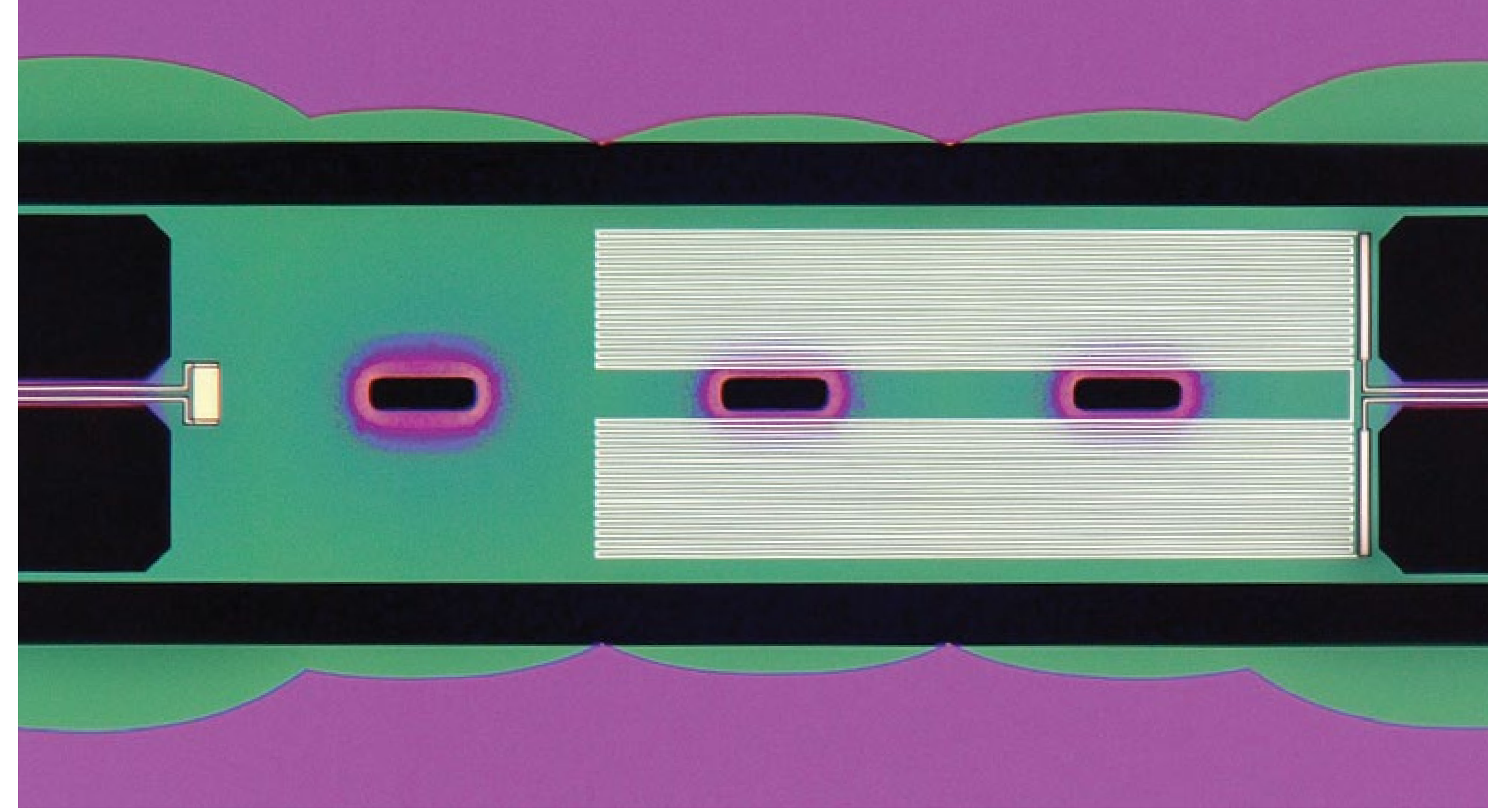
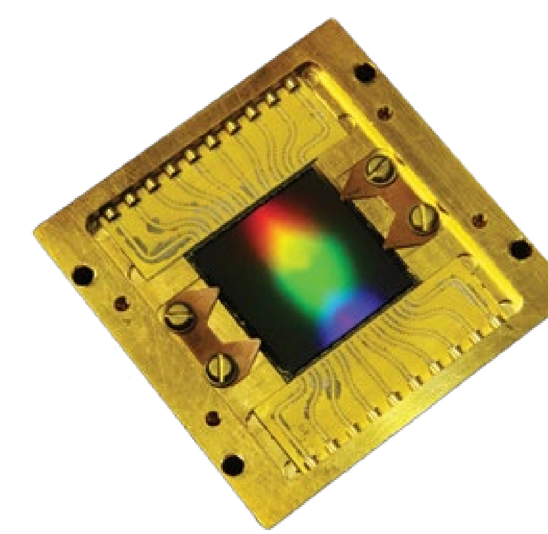
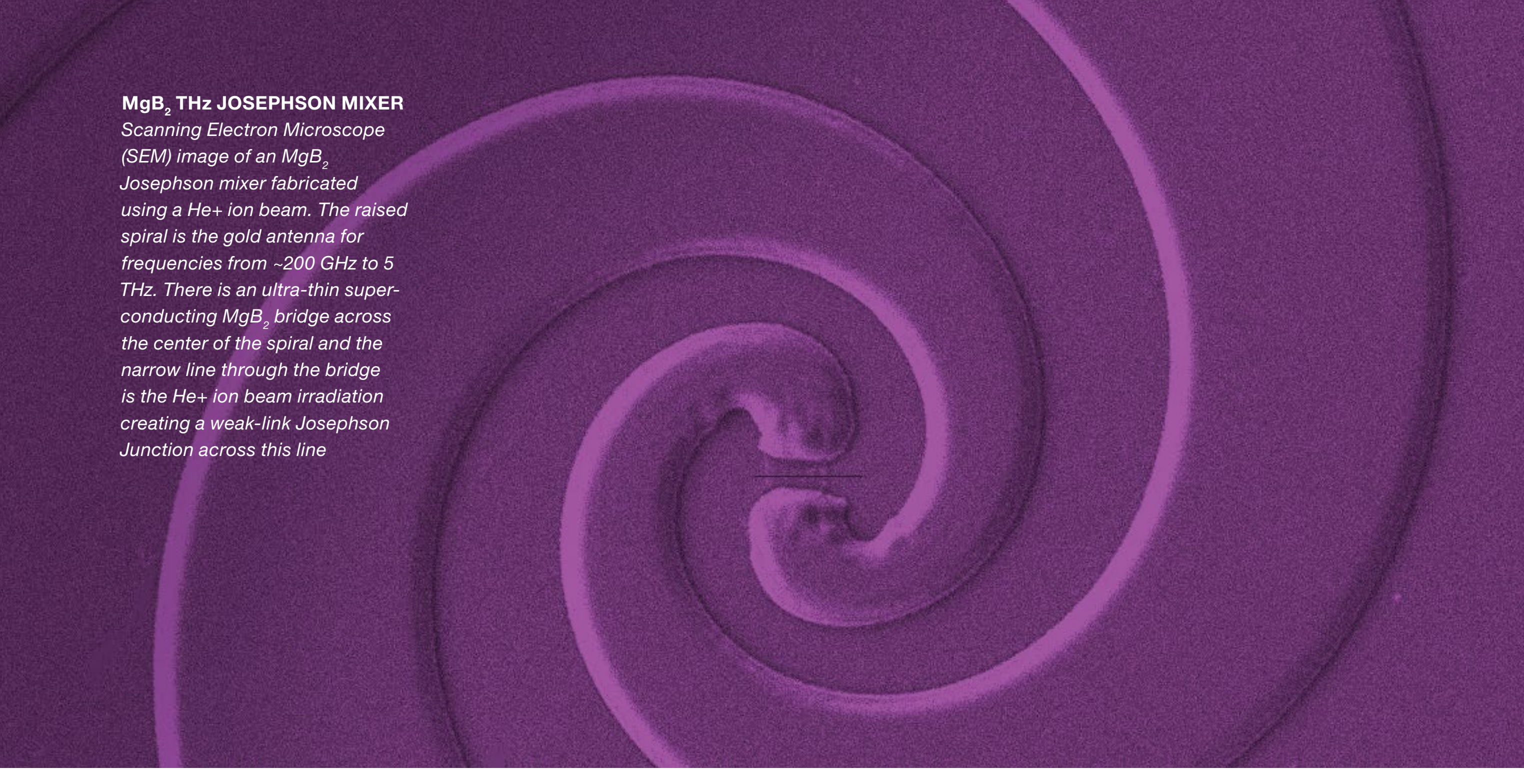
MKID ARRAY
MKID array for passive, polarization-sensitive imaging at 150 GHz



TKIDS
TKIDs under development for millimeter-wave astrophysics. As with traditional KIDs, TKIDs are built around high-Q resonators with resonances that shift under loading. TKIDs differ from KIDs in that the inductors are membrane-isolated and function as thermometers in a bolometer.



MKID IMAGING CHIP
20,000-pixel MKID imaging chip fabricated in MDL for the MKID Exoplanet Camera (MEC) on the Subaru telescope in Hawaii, fielded by Professor Ben Mazin's group at UC Santa Barbara



MgB_2 THz JOSEPHSON MIXER
Scanning Electron Microscope (SEM) image of an MgB_2 Josephson mixer fabricated using a He+ ion beam. The raised spiral is the gold antenna for frequencies from ~200 GHz to 5 THz. There is an ultra-thin superconducting MgB_2 bridge across the center of the spiral and the narrow line through the bridge is the He+ ion beam irradiation creating a weak-link Josephson Junction across this line

on the 315-inch Subaru telescope in Hawaii to search for habitable exoplanets. Another ongoing development is kinetic inductance bolometers based on the high temperature superconductor, yttrium barium copper oxide. The goal of this work is to achieve low-noise operation at 50–55K to provide the basis for a passively cooled Fourier-transform infrared spectrometer for outer planet missions. Development also continues on the quantum capacitance detector, which has achieved record sensitivity, making it a promising candidate for future far-infrared missions.

A microwave frequency version of the kinetic inductance traveling-wave parametric amplifier developed in MDL has demonstrated quantum limited sensitivity over nearly an octave of bandwidth. New designs are targeting the Ka-band, for Deep Space Network applications and cosmic microwave background measurements, and the W band, for application to millimeter-wave interferometers such as the Atacama Large Millimeter Array. Nonlinear superconducting transmission lines can efficiently generate harmonics of an input waveform with an efficiency approaching unity for a narrow band of > 50 percent over a bandwidth of tens of percent. This effect has been harnessed to produce highly efficient multipliers for frequencies up to ~1 THz using niobium titanium nitride transmission lines. This range may be extended using other superconductors. Triplers for an initial demonstration at 300 GHz (output frequency) have been designed and are currently in fabrication. Thermopile arrays for far IR — IR imagers are an example of a non-superconducting technology that grew out of early group activity on superconducting sensors and continues to this day. Recent applications include far-infrared spectrometers for the Radiation Budget Instrument (RBI) and the planned Polar Radiant Energy in the Far Infrared Experiment (PREFIRE). Superconducting nanowire single photon detectors (SNSPDs) provide the highest available sensor performance from ultraviolet to mid-infrared wavelengths. MDL has been a world leader in the development of this unique technology, currently holding world records for SNSPD detection efficiency, time resolution, active area, and dark counts. JPL SNSPDs are to be employed in the ground terminal of the Deep Space Optical Communication (DSOC) project in 2022.

HIGHLIGHT

MgB_2 in the Microdevices Laboratory

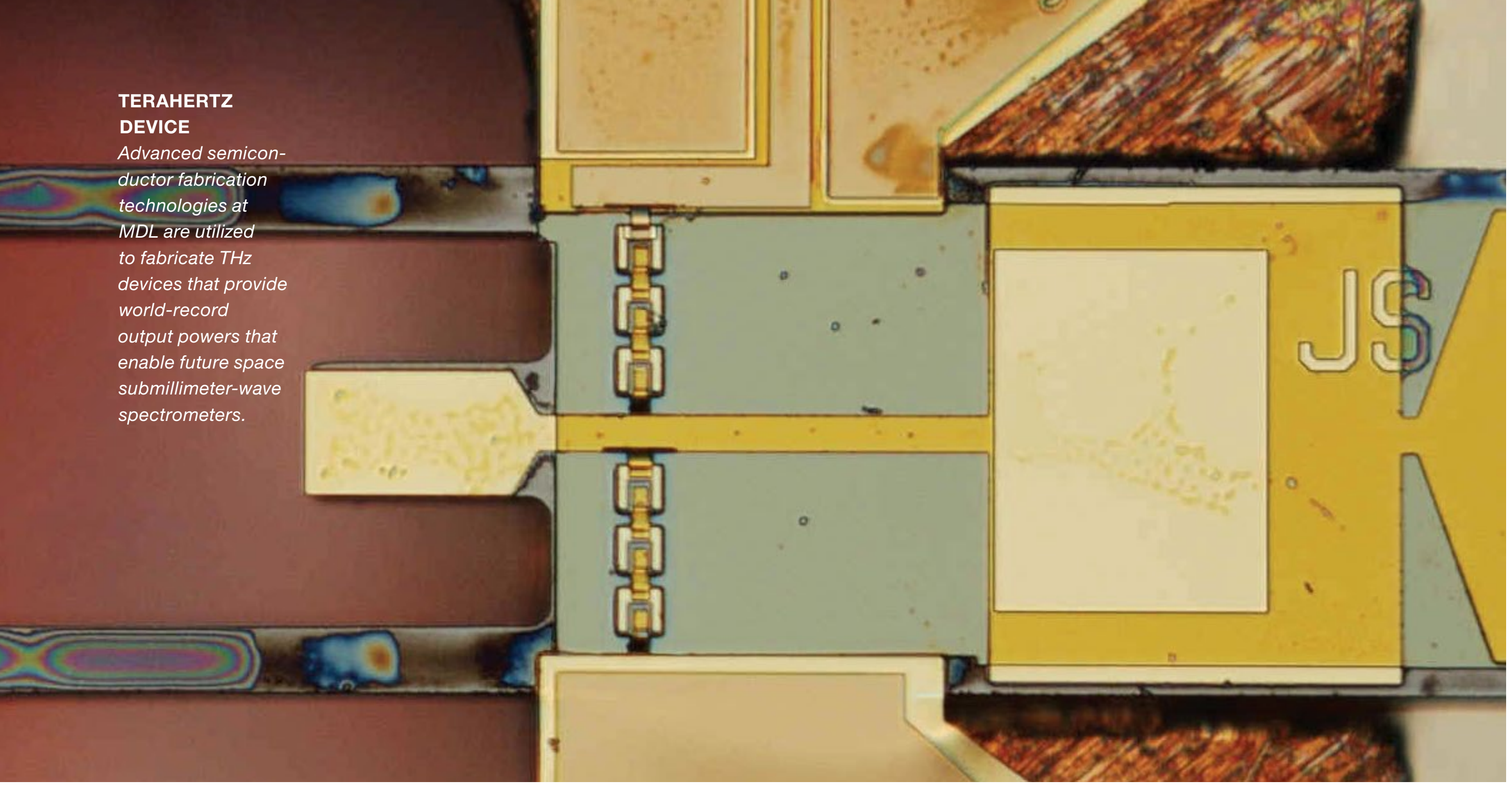
Magnesium diboride (MgB_2) is a simple metallic compound discovered in 2001 to be superconducting. Currently, ultra-thin films (5–20 nanometers) of this material with characteristics similar to those in the bulk have been achieved. The moderate critical temperature around 40K and large superconducting gap are very useful for high-frequency (THz) superconducting electronics with space applications.

The primary NASA/JPL application for these films is in THz mixers (hot-electron bolometers and Josephson junctions) for astrophysics. Proof-of-concept demonstrations of such mixers have recently been made in the 0.6–4.3 THz range. Operation at temperatures of 15–20 K with high sensitivity and an intermediate frequency bandwidth nearly three times larger than the state-of-the-art (> 7 GHz) are important benefits of the MgB_2 material. These devices were developed at MDL in collaboration with Temple University, which grew the superconducting thin films. Researchers are currently working to develop waveguide-based mixers on silicon membranes in order to enable multi-pixel heterodyne receivers for future instrument concepts including the Heterodyne Receiver for the Origins Space Telescope (HERO). Other emerging applications include mid-infrared heterodyne detectors, optical single-photon detectors, phased antenna arrays, frequency multipliers, and parametric amplifiers.

Recently, MDL researchers began developing MgB_2 thin film growth using an atomic layer deposition (ALD) system to emulate the process used at Temple University. The goal is to enable large-area deposition on silicon substrates (> 3” diameter) for fast throughput processing. Large area film with improved uniformity will allow application of advanced projection lithography in order to achieve submicron-size MgB_2 devices with good yield. This research at JPL is funded by NASA’s Nancy Grace Roman Fellowship in Astrophysics.

THz JOSEPHSON JUNCTION MIXER BASED ON MgB_2

A novel mixer recently set a record for high-frequency operation of a Josephson Junction detector. The mixing occurs in a weak link within a small superconducting bridge where the energy gap is large due to the particular orientation of the junction and specific properties of MgB_2.



TERAHERTZ DEVICE
Advanced semiconductor fabrication technologies at MDL are utilized to fabricate THz devices that provide world-record output powers that enable future space submillimeter-wave spectrometers.

SUBMILLIMETER DEVICES

Novel circuit designs and advanced chip fabrication technology from MDL have demonstrated more than 1 mW of output power at 1 THz

The Microdevices Laboratory (MDL) specializes in developing and implementing submillimeter-wave receivers and terahertz remote sensing technologies for a variety of applications. The primary focus is to develop components and technologies to enable space-borne, high-resolution heterodyne spectrometers for Earth remote sensing missions, planetary missions, and astrophysics observatories. Heterodyne technology allows one to map and/or detect unique molecular signatures with very high-spectral resolution over a wide range of wavelengths.

During the past year, we have developed superconductor-insulator-superconductor (SIS) tunnel junction receivers in the 500 GHz range with close to quantum-limited sensitivity. Similarly, novel materials are being investigated to produce hot-electron mixers that will allow astrophysicists to probe deeper into the interstellar medium for answers concerning star formation.

Semiconductor based low-parasitic Schottky diodes continue to be fabricated at MDL that provide high-efficiency and impressive output power. These coherent sources are needed to pump heterodyne receivers as well as to be deployed in submillimeter-wave radars—technologies that are being advanced to design and build the next generation of instruments for space exploration. From investigating water isotopes and the deuterium-to-hydrogen ratio of water found in the universe to investigating star-forming regions, submillimeter-wave technology provides a unique tool for better understanding the cosmos.

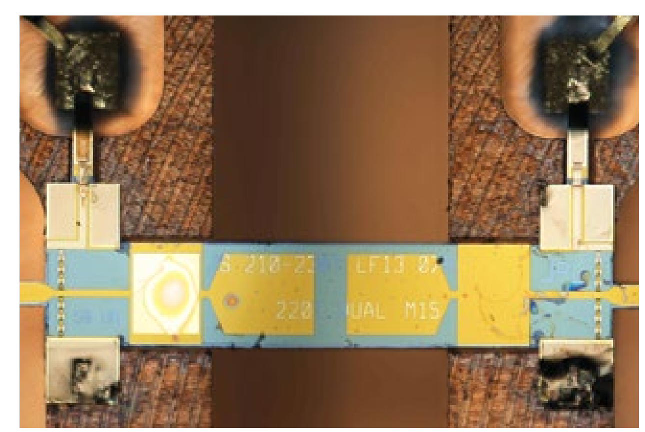
HIGHLIGHT

Closing the "Terahertz Gap" with Room-Temperature, All-Solid-State Local Oscillator Sources

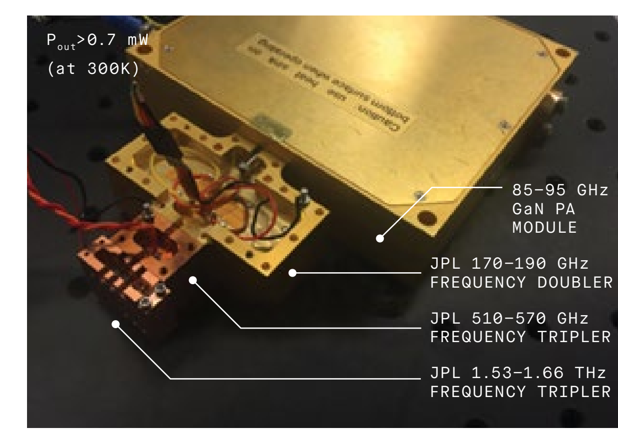
MDL recently demonstrated room-temperature, all-solid-state local oscillator sources with output power levels more than 10 times higher than the previous state-of-the-art. These local oscillator sources are Schottky diode–based frequency multiplied chains featuring a novel JPL-patented circuit topology called on-chip power-combining. This concept, together with a precise optimization of the devices for high-power operation, yield an improvement in power-handling capabilities by one order of magnitude.

These results represent a major breakthrough in power generation at submillimeter-waves and terahertz frequencies and contribute enormously to close the so-called "terahertz gap." Prototypes at 180, 230, 340, 530, and 1000 GHz have been designed, fabricated, assembled, and tested at JPL. Record output power of 600, 120, 40, 30, 2.0, and 0.7 milliwatts have been measured, respectively. The local oscillator sources operate at room temperature and exhibit state-of-the art conversion efficiencies and frequency bandwidths of around 15–20 percent. These Schottky-based sources have important advantages over other technologies used such as quantum cascade lasers. For example, no cryogenic cooling is required and they have frequency tunability over a 15–20 percent bandwidth, thermal stability, Gaussian radiation patterns, and at least a 10 times reduction in size and DC power consumption. The new high-power JPL 1.6 THz local oscillator source is shown below. It has a DC power consumption of around 20 watts and produces and output power of >0.7 milliwatts at 1.6 THz at room temperature. Further improvement can be achieved by cooling the source down to 120 K.

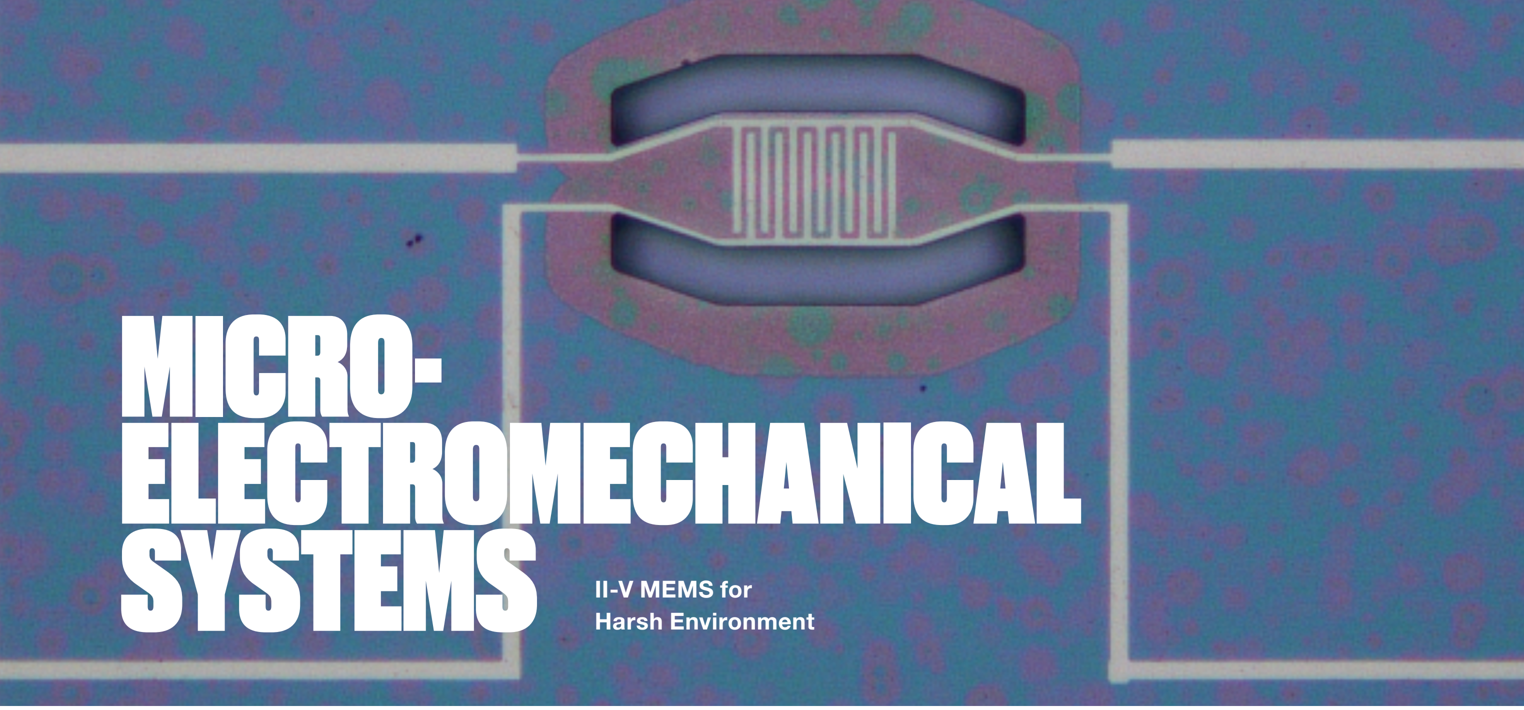
With these sources available, high-resolution THz imaging radar systems and high-data bit rate communication systems are now possible. For astrophysics, heterodyne array receivers beyond 1 THz are necessary to map galaxies in the search for nitrogen, oxygen, carbon, and other tracers of star-forming regions to fully understand how solar systems form and evolve.



TRIPLER DESIGN
A dual on-chip power-combined gallium arsenide 527 GHz tripler design is combined with a compact housing able to handle more than 500 milliwatts and produce a world-record output power of 30 milliwatts.

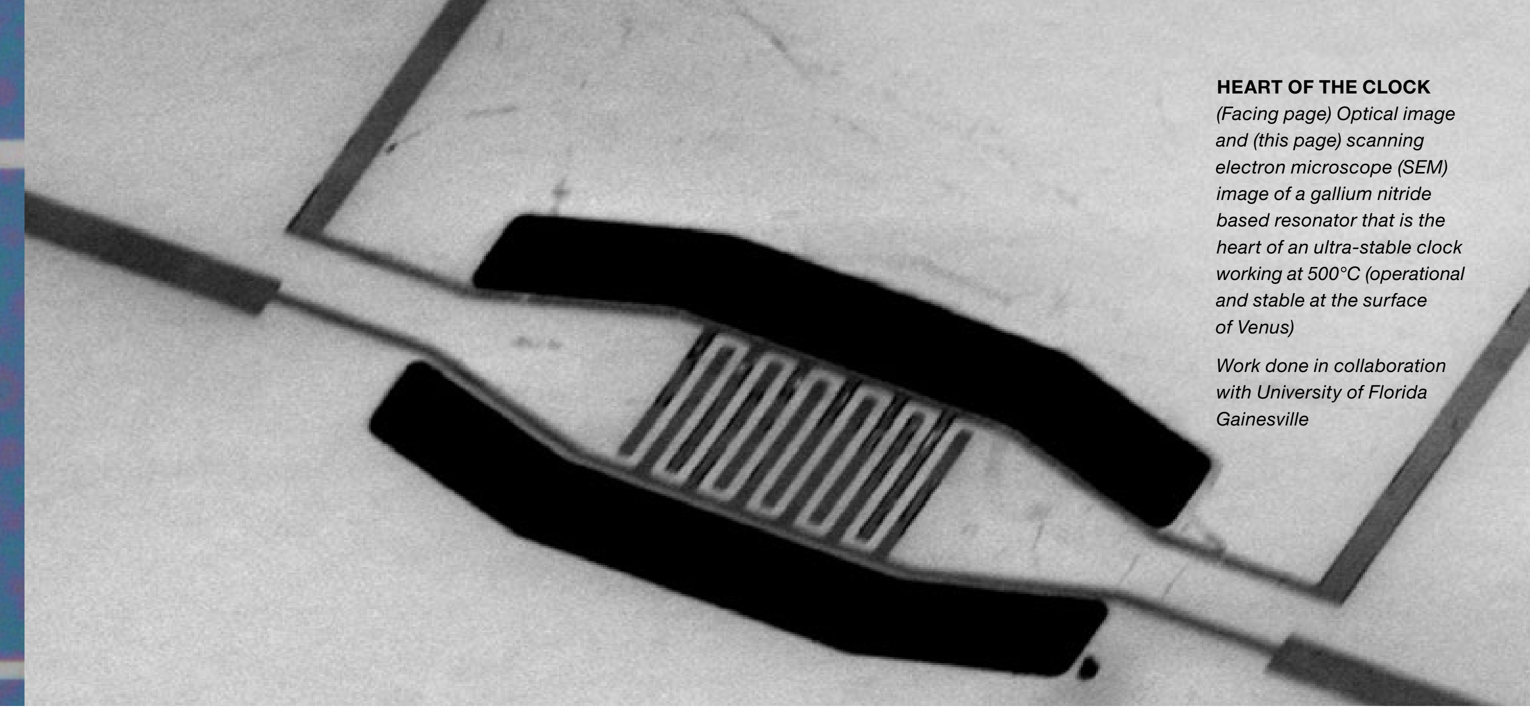


LOCAL OSCILLATOR SOURCE
High-power 1.6 THz frequency multiplied local oscillator source recently demonstrated at JPL, exhibiting a world-record output power of 0.7 milliwatts at room-temperature operation, which is a 10 times improvement over the previous state-of-the-art.



MICRO-ELECTROMECHANICAL SYSTEMS

II-V MEMS for Harsh Environment



HEART OF THE CLOCK
(Facing page) Optical image and (this page) scanning electron microscope (SEM) image of a gallium nitride based resonator that is the heart of an ultra-stable clock working at 500°C (operational and stable at the surface of Venus)

Work done in collaboration with University of Florida Gainesville

The Advanced Optical and Electromechanical Microsystems group within the Microdevices Laboratory (MDL) was formed to take advantage of combined expertise in microfabrication, nanomaterials, and packaging technologies to develop miniature instruments, sensors, and microsystems for space flight. The long-term goal of the group is to deliver smaller payloads that are either stand-alone, highly capable, or distributed and networked with dedicated capability for planetary exploration. To that end, the group focus is on employing novel techniques, designs, and materials to produce sensors and microsystems that can accurately measure unique signatures (e.g., magnetic field and seismic signals) of planetary bodies or electronic components that can withstand prolonged extreme environments.

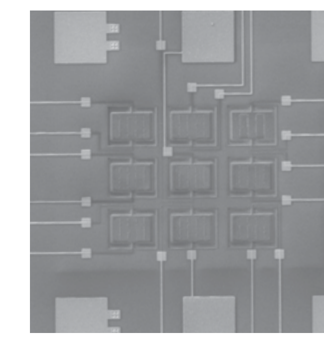
The group also specializes in resonant microelectromechanical systems (MEMS) devices, unique micro-machined components to enhance the performance of existing instruments or to enable new measurements.

HIGHLIGHT

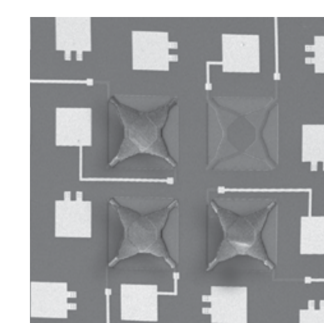
Microsystems for Frequency Control and Frequency Shifting Sensors in Harsh Environments

Missions to hot planets, such as Venus or Mercury, have traditionally been extremely short in duration and have had a very narrow scope mainly due to the unavailability of sensors and readout electronics that can survive the extreme environments of those planets. To address this problem, MDL is working to develop several sensor technologies that can survive at extreme temperatures and in high-radiation environments. These new sensors use III-V piezoelectric compounds that are chemically inert and can be used not only for making high-temperature-tolerant sensors but also for building electronics that can work at temperatures up to 1,000 degrees Celsius. Sensors and microsystems such as infrared (IR) detectors and high-temperature tolerant clocks are currently being developed as part of this effort: the IR detectors are sensitive to a broad range of spectra from ultraviolet to far-IR with ultra-low-noise performance and frequency multiplexing capability. The frequency of the detectors shifts proportionally to the amount of absorbed IR power. These detectors are higher performance alternatives to microbolometers and offer lower cost, lower power, and smaller-size alternatives to kinetic inductance detectors with similar frequency multiplexing capabilities and without the need to be operated at a specific and narrow temperature range defined by the superconducting transition temperature. Each pixel of the detector array is composed of an acoustic resonator with high-quality factor (Q) and high-temperature coefficient of frequency (TCF). The resonator geometry is engineered such that their TCF is not limited by the material properties of the material set in the resonating stack. Instead, the resonator exhibits TCF in the order of 1,000 parts per million per degree Celsius, which is 30-fold larger than the TCF if defined by the temperature coefficient of elasticity. These detectors need not be cooled to be functional, but their background noise will be significantly suppressed at low temperatures and their Qs will become even higher. This means that, depending on the application, they can be cooled to any temperature to meet the science need. In addition, nanofabrication allows integration of thousands of pixels to form a large imaging array. A provisional patent has been filed on the design of the resonant pixels.

The high-temperature clock technology uses a similar material stack but its properties are engineered to achieve near-zero shift in frequency with a change in temperature. Currently, the group, in collaboration with Stanford University and University of Florida, is developing clocks that are stable at temperatures up to 500 degrees Celsius in indium aluminum nitride/Gallium nitride (InAlN/GaN) material stacks. InAlN/GaN high-mobility transistors have been shown to work at temperatures as high as 1,000 degrees Celsius. This work, supported by a NASA HOTTech Award, is aimed at demonstrating high-temperature-tolerant clock technologies using the same stack for the first time to enable data transfer at high temperatures. Since the data collected from any probe, lander, explorer, or sensor in a harsh environment needs to be transferred to the main spacecraft in a robust fashion, realizing a local clock with a stable frequency output is the most crucial part of such a communication system.



RESONANT DETECTOR ARRAY
Scanning electron microscope (SEM) image of a resonant piezoelectric infrared detector array with a very wide dynamic range of operation (wide temperature range of operation)



RESONANT DETECTOR ARRAY
Scanning electron microscope (SEM) image of a stress engineered resonant array with high sensitivity and very wide dynamic range of operation suitable for operation in extreme environments

APPENDIX

JOURNAL PUBLICATIONS: IN A JOURNAL FORMAT

1. P. Mouroulis, and R. O. Green. “Review of high fidelity imaging spectrometer design for remote sensing,” Optical Engineering, vol. 57, no. 4, 040901, 2018.

2. D. R. Thompson, B. H. Kahn, R. O. Green, S. A. Chien, E. M. Middleton, and D. Q. Tran. “Global spectroscopic survey of cloud thermodynamic phase at high spatial resolution, 2005–2015,” Atmospheric Measurement Techniques, vol. 11, no. 2, 1019, 2018.

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1. C.J. Cochrane, “Magnetic Field Sensing with Quantum Centers in SiC,” Society for Brain Mapping and Therapeutics (SMBT) Annual Congress, Los Angeles, CA 4/15/2018. Invited

2. S.R. Cheng, D. Budzyn, and S. Nikzad, “UV/VIS Fluorescence and Reflectance Measurements using Delta-Doped Silicon Arrays for Medical and Bio Applications,” in Biosensing Techniques with Advanced Materials, American Physical Society, Los Angeles, Mar. 2018.

APPENDIX, CONT.

3. E. E. Wollman, B. A. Korzh, J. P. Allmaras, A. D. Beyer, S. Frasca, R. M. Briggs, E. Ramirez, and M. D. Shaw, "Applications of superconducting nanowire single-photon detectors: deep space optical communication, UV photon counting, and ultra-high time resolution," Proc. SPIE 10659, Advanced Photon Counting Techniques XII. April 18-19, 2018. Orlando, FL.

4. J.W. Kooi, D.J. Hayton, B. Bumble, H.G. LeDuc, P. Echternach, A. Sakalare, J. Kawamura, G. Chattopadhyay, and I. Medhi, "Submillimeter and Terahertz Receiver Technology for the Detection of Water Isotopes on Cometary Bodies," Presentation W 5.2 at 29th IEEE International Symposium on Space Terahertz Technology (ISSTT2018), Pasadena, CA, Mar. 2018.

5. A. Jewell, A. Carver, S. Nikzad, and M. Hoenk "Two-dimensional N-type Doping in Silicon with Antimony," Materials Synthesis, American Physical Society, Los Angeles, Mar. 2018.

6. A. Jewell, M. Hoenk, D. Hitlin, M. McClish, A. Carver, T. Jones, S. Nikzad "Silicon sensors with integrated UV filters for fast scintillation detectors and solar-blind imaging systems," John Hennessy, in Instrumentations and Measurements II, American Physical Society, Los Angeles, Mar. 2018.

7. L. D. Bell, et al., "Progress in Cesium-Free III-Nitride Photocathodes Based on Control of Polarization Charge," March Meeting of the American Physical Society, Los Angeles, California, Mar. 2018.

8. M. Rais-Zadeh, "Microsensors and systems for missions to hot planets," 2018 CMOS Emerging Technologies Research Symposium, invited plenary talk, Vancouver, Canada, May 2018.

9. M. Rais-Zadeh, "GaN Sensors and Electronics for Missions to Hot Planets," ECSMeeting Abstracts, 1403-1403, May 2018.

10. M. Rais-Zadeh, "Gallium Nitride MEMS for Sensing and Frequency Control," Texas Instrument/U. Texas Dallas, Apr. 2018.

11. M. Rais-Zadeh, "Application of phase change materials in photonics and reconfigurable RF microsystem," MRS 2018 Spring Meeting & Exhibit, invited, Phoenix, Apr. 2018.

12. S. Nikzad, J. Hennessy, A. Jewell, A. Kiessling, M. Hoenk, A. Carver, R. Morgan, S. Martin, S. Cheng "Detectors w High Efficiency & Low Noise for Exoplanet Studies & Cosmology," Poster Session III, American Physical Society, Los Angeles, Mar. 2018.

13. A. Carver, J. Hennessy, D. Wilson, A. Jewell, P. Mouroulis, S. Nikzad, "Advanced Ultraviolet Imaging Spectrometer for Planetary Studies," in Poster Session III, American Physical Society, Los Angeles, Mar. 2018.

14. D. Bell, S. Nikzad, E. Rocco, J. Marini, and S. Shahedipour-Sandvik, "Progress in Cesium-Free III-Nitride Photocathodes Based on Control of Polarization Charge," in Semiconductor Surfaces and Nanostructures, American Physical Society, Los Angeles, Mar. 2018.

15. C.J. Cochrane, "Magnetic Field Sensing with 4H SiC Diodes—Nitrogen vs Phosphorous Implantation," International Conference on Silicon Carbide and Related Materials (ICSCRM), Washington D.C., Sept. 2017.

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17. C.J. Cochrane, European Conference on Silicon Carbide and Related Materials (ECSCRM), "Three-axis SiC magnetoresistive based magnetometer", Halkidiki, Greece, Sept. 2016.

18. C.J. Cochrane, "Self-calibrating solid-state SiC magnetometer for planetary field mapping," 3rd International Workshop on Instrumentation for Planetary Missions (IPM), Pasadena CA, Oct. 2016.

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BOOK CONTRIBUTIONS

M. Rais-Zadeh, D. Weinstein, "Gallium Nitride for M/NEMS," Piezoelectric MEMS Resonators, 73–98, 2017.

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PATENTS AWARDED

H. Manohara, L Del Castillo, M. Mojarradi, "Micro- and Nanoscale Capacitors that Incorporate an Array of Conductive Elements Having Elongated Bodies," U.S. Patent: 9,406,442, Issued 08/02/2016.

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B. Kateb and S. Nikzad, International Brain Mapping, Intra-Operative Surgical Planning Foundation and California Institute of Technology, 2017. Multi modality brain mapping system (MBMS) using artificial intelligence and pattern recognition. U.S. Patent: 9,754,371.

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R. M. Briggs; C. F. Frez; S. Forouhar, "Index-Coupled Distributed-Feedback Semiconductor Quantum Cascade Lasers Fabricated Without Epitaxial Regrowth," U.S. Patent: 9,991,677, Issued: 6/5/2018

SPECIAL RECOGNITION

a. H. M. Manohara, NASA Exceptional Technology Achievement Medal for leading the development of the world's smallest 3D imaging multi-angle endoscopic tool with unprecedented panning ability.

b. H. M. Manohara, JPL Explorer Award for excellence in leadership and interaction with industry and the development of advanced dual use technology.

c. A. Khoshakhlagh, JPL Lew Allen Award for technical innovation in developing the novel Gallium-free antimonies super lattice epitaxial material.

d. D. Ting, A. Soibel, A. Khoshakhlagh, S. Rafol, C. Hill, A. Fisher, B. Pepper, S. Keo, E. Luong, J. Mumolo, J. Liu, and S. Gunapala, MSS (Military Sensing Symposia) Herschel Award for NASA's Jet Propulsion Laboratory HOT-BIRD (High Operating Temperature Barrier Infrared Detectors) Technology, March 2018.

e. JPL Ed Stone Award for outstanding publication:

- C.J. Cochrane "Vectorized magnetometer for space applications using electrical readout of atomic scale defects in silicon carbide," Nature Scientific Reports 6, 37077; doi: 10.1038/srep37077. 2016.
- Ryan Briggs "Low-dissipation 7.4-μm-wavelength single-mode quantum cascade lasers fabricated without epitaxial regrowth," Optics Express, vol. 24, no. 13, 14589, 2016.

f. S. Gunapala, SPIE George W. Goddard Award in recognition of exceptional achievement in optical or photonic instrumentation for aerospace, atmospheric science, or astronomy, Aug. 2018.

g. S. Gunapala, Presidential Honors; The Sri Lanka Ranjana titular conferred to non-nationals was conferred on, scientist Dr. Sarath Gunapala, Sri Lanka, Mar. 2017.

h. S. Nikzad, fellow of the National Academy of Invention. For inventive work extending the UV response in CCDs and more recently, CMOS image sensors, using low temperature MBE and CVD techniques.

i. W. Holmes, Planck Scientist. The Planck team won the prestigious Gruber prize.

PROFESSIONAL SOCIETY DISTINCTION

a. D. Ting, IEEE Photonics Society Distinguished Lecturer

b. M. Rais-Zadeh, IEEE Electron Device Society Distinguished Lecturer

c. M. Rais-Zadeh, Technical program committee chair of the 2018 Hilton Head Workshop and General chair of the same workshop in 2020.

d. S. Forouhar, SPIE Quantum Sensing and Nano Electronics and Photonics committee member since 2015.

MDL EQUIPMENT COMPLEMENT

Material Deposition

- Thermal Evaporators (5)
- Electron-Beam Evaporators (7)
- Angstrom Engineering Indium-metal Evaporator
- Ultra-High-Vacuum (UHV) Sputtering Systems for Dielectrics and Metals (3)
- Ultra-High-Vacuum (UHV) Sputtering Systems for Superconducting Materials (3)
- AJA Load Locked Thermal Co-Evaporator for Broadband IR Bolometer Depositions
- PlasmaTherm 790 Plasma Enhanced Chemical Vapor Deposition (PECVD) for Dielectrics with Cortex Software Upgrade
- Oxford Plasmalab System 100 Advanced Inductively Coupled Plasma (ICP) 380 High-Density Plasma Enhanced Chemical Vapor Deposition (HD PECVD) System for Low Temperature Dielectric Growths
- Oxford Plasmalab 80 OpAL Atomic Layer Deposition (ALD) System with Radical Enhanced Upgrade
- Beneq TFS-200 Atomic Layer Deposition (ALD) System with Meaglow Plasma Source Upgrade
- Tystar (150mm /6-inch) Low-Pressure Chemical Vapor Deposition (LPCVD) with 2 Tubes for
  —Low Stress Silicon Nitride
  —Atmospheric Wet/Dry Oxidation
- Carbon Nanotube Furnace Systems (2)
- Electroplating Capabilities
- Molecular-Beam Epitaxy (MBE)
  —Veeco GEN200 (200mm/8-inch) Si MBE for UV CCD Delta Doping (Silicon)
  —Veeco GEN200 (200mm/8-inch) Si MBE for UV CCD Delta Doping (Silicon)
  —Veeco Epi GEN III MBE (Antimonide Materials)
  —Riber MBE for UV CCD Delta Doping (Silicon)
  —Riber Device MBE (GaAs)

Lithographic Patterning

- Electron-Beam (E-beam) Lithography: JEOL JBX 9500FS E-beam lithography system with a 3.6 nm spot size, switchable 100,000 & 48,000 volt acceleration voltages, ability to handle wafers up to 9 inches in diameter, and hardware and software modifications to deal with curved substrates having up to 10 mm of sag
- GCA Mann Wafer Stepper with custom stage allowing different sizes and thicknesses of wafers (0.7-μm resolution)
- Canon FPA3000 i4 i-Line Stepper (0.35-μm resolution)
- Canon FPA3000 EX3 Stepper with EX4 Optics (0.25-μm resolution)
- Canon FPA3000 EX6 DUV Stepper (0.15-μm resolution)
- Contact Aligners:
  —Karl Suss MJB3 with backside IR
  —Suss MA-6 (UV300) with MO Exposure Optics upgrade
  —Suss BA-6 (UV400) with jigging supporting Suss bonder
- Wafer Track/Resist/Developer Dispense Systems:
  —Suss Gamma 4 Module Cluster System
  —Site Services Spin Developer System
  —SolarSemi MC204 Microcluster Spin Coating System with Hot Plate & Dispense Upgrades
- Yield Engineering System (YES) Reversal Oven
- Ovens, Hotplates, furnaces, and Manual Spinners (including 2 Solitec 5110C spinners, and a Suss RC8 Spin Coater)

Dry Etching

- Commonwealth IBE-80 Ion Mill
- Branson Plasma Ashers (2)
- Tepla PP300SA Microwave Plasma Asher
- Fluorine-based Plasma Etching Systems
- STS Deep Trench Reactive Ion Etcher (DRIE) with SOI Upgrade
- PlasmaTherm Versaline Deep Silicon Etcher (DSE/DRIE)
- Unaxis Shuttleline Load-Locked Fluorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm APEX SLR Fluorine-based ICP RIE with Laser End Point Detector
- Plasmaster RME-1200 Fluorine RIE
- Plasma Tech Fluorine RIE
- STJ RIE for Superconductors
- Custom XeF2 etcher
- Oxford PlasmaPro 100 Cobra Black Silicon Load-Locked Cryo Etching / Atomic LayerEtching / Bosch Etching System.

Chlorine-based Plasma Etching Systems

- Unaxis Shuttleline Load-Locked Chlorine Inductively Coupled Plasma (ICP) RIE
- PlasmaTherm Versaline Chlorine-based ICP Etcher

Wet Etching & Sample Preparation

- RCA Acid Wet Bench for 6-inch Wafers
- Solvent Wet Processing Benches (7)

APPENDIX, CONT.

- Rinser/Dryers for Wafers including Semitool 870S Dual Spin Rinser Dryer
- Chemical Hoods (7)
- Acid Wet Processing Benches (8)
- Tousimis 915B Critical Point Dryer
- Rapid Thermal Processors/ Contact Alloyers (2)
- Polishing and Planarization Stations (5)
- Strasbaugh 6EC Chemical Mechanical Polisher
- Precitech Nanonform 250 Ultra Diamond Point Turning System
- SET North America Ontos 7 Native Oxide (Indium Oxide) Removal Tool with Upgrade
- Novascan UV8 Ultraviolet Light Ozone Cleaner
- New Wave Research EzLaze 3 Laser Cutting System
- Indonus HF VPE-150 Hydrofluoric Acid Vapor Phase Etcher
- Laurell Technologies Dilute Dynamic Cleaning System (DDS), Model EDC 650 – a Dilute HF/Ozonated DI Water Spin Cleaning System with MKS Instruments Liquizon Ozonated Water Generator
- Osiris Fixxo M200 TT Wafer Mounting Tool
- Surfx Atomflo 500 Argon Atmospheric Plasma Surface Activation System for wafer bonding

Packaging

- SET FC-300 Flip Chip Bump Bonder
- Karl Suss Wafer Bonder
- Electronic Visions AB1 Wafer Bonder
- EVG 520Is Semi-Automatic Wafer Bonding System
- Finetech Fineplacer 96 “Lambda” Bump Bonder
- Thinning Station and Inspection Systems for CCD Thinning
- Wire Bonding
- DISCO 320 and 321 Wafer Dicers (2)
- Tempress Scriber
- Pick and Place Blue Tape Dispenser System
- Loomis LSD-100 Scriber Breaker
- SCS Labcoater 2 (PDS 2010) Parylene Coating System

Characterization

- Profilometers (2) (Dektak 8 & Alphastep 500)
- Frontier Semiconductor FSM 128 Film Stress Measuring system Frontier Semiconductor FSM 128-NT (200mm/8-inch) Film Stress and Wafer Bow Mapping System
- LEI 1510 Contactless Sheet Resistance Tool
- FISBA μPhase 2 HR Compact Optical Interferometer
- Senetech SE 850 Multispectral Ellipsometer
- Horiba UVSEL 2 (190-2100 nm) Ellipsometer
- Filmetrics F20-UV (190-1100 nm) Thin Film Spectrometer Measurement System
- Filmetrics F40-UVX (190-1700 nm) Thin Film Spectrometer Measurement System with Microscope
- Dimension 5000 Atomic Force Microscope (AFM)
- Park Systems Inc. NX20 Atomic Force Microscope (AFM)
- KLA-Tencor Surfscan 6220 Wafer Particle Monitor
- JEOL JSM-6700 Field Emission SEM with EDX
- Nikon & Zeiss Inspection Microscopes with Image Capture (3)
- Keyence VHX-5000 Digital Microscope with low power lens
- McBain BT-IR Z-Scope IR Microscope Workstation
- Olympus LEXT 3D Confocal Microscope
- Mitaka NH-5Ns 3D Profiler
- Electrical Probe Stations (4) with Parameter Analyzers (2)
- RPM2035 Photoluminescence Mapping System
- Fourier Transform Infrared (FTIR) Spectrometers (3) including Bruker Optics Vertex 80 FTIR
- PANalytical X’Pert Pro MRD with DHS High Temperature Stage X-ray Diffraction System
- Surface Science SSX501 XPS with Thermal Stage
- Custom Ballistic Electron Emission Microscopy (BEEM) System
- Custom UHV Scanning Tunneling Microscope (STM)
- Nanometrics ECV Pro Profiler
- VEECO/WYKO NT 9300 Surface Profiler (including 50X optics)
- Zygo ZeMapper non-contact 3D Profiler
- Thermo Scientific LCQ Fleet CE / MS (Capillary Electrophoresis / Mass Spectrometer) System

THE TEAM AT MDL

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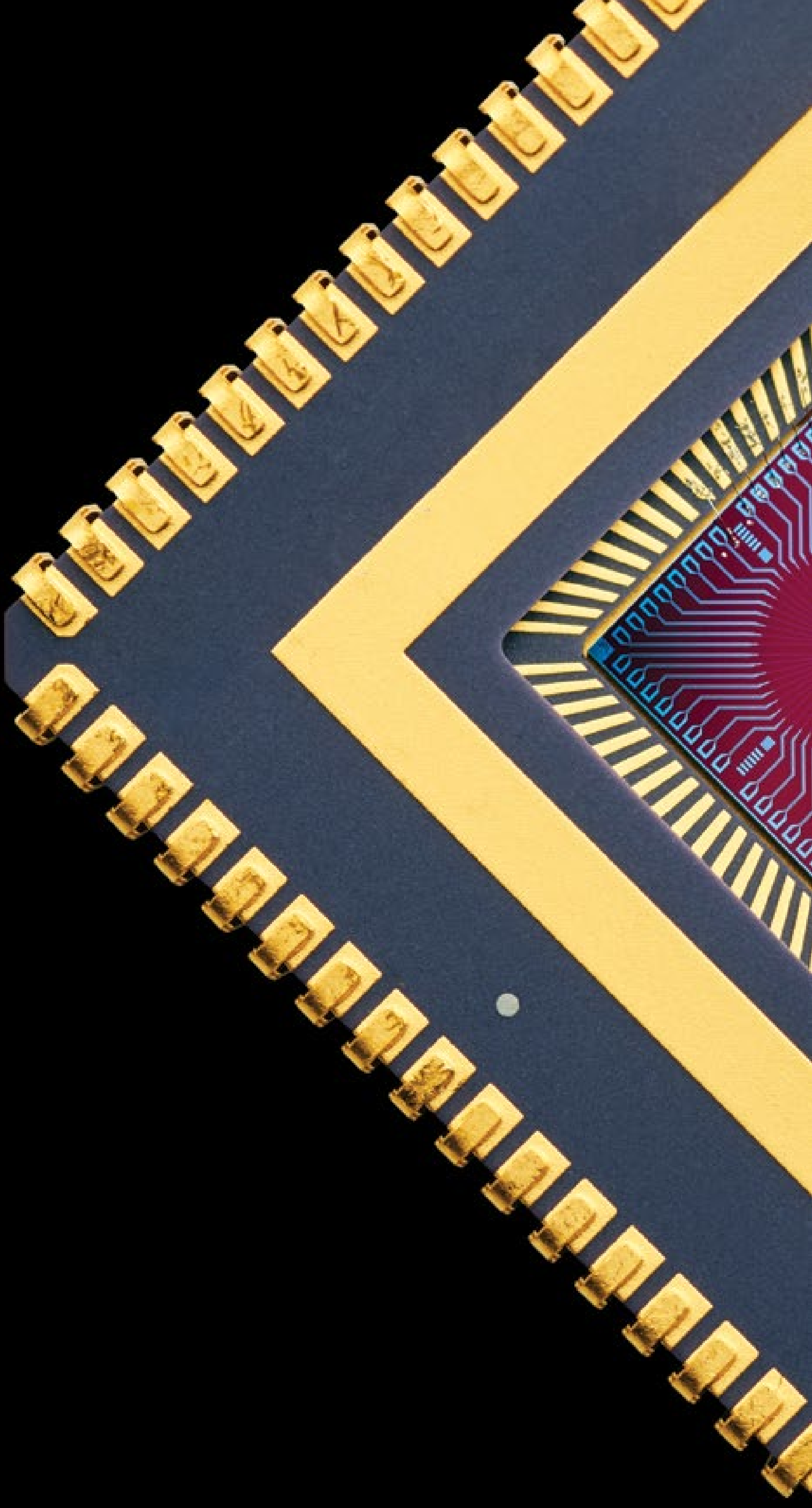

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