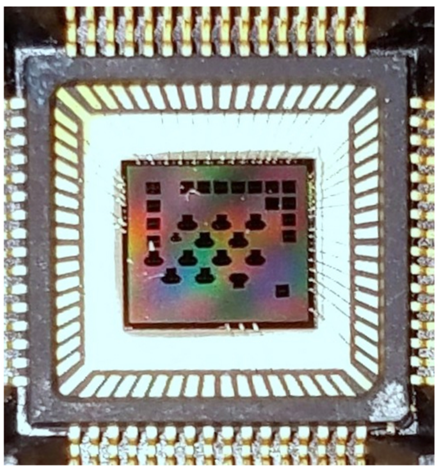
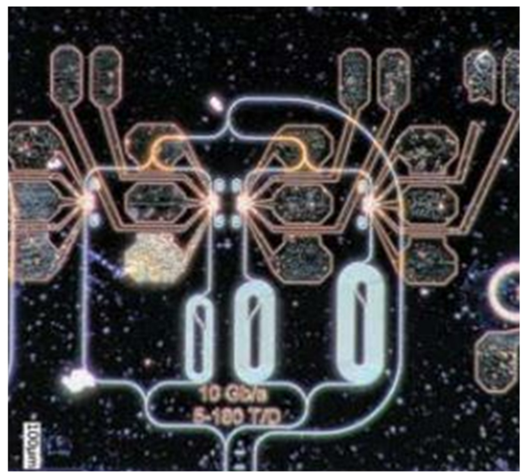
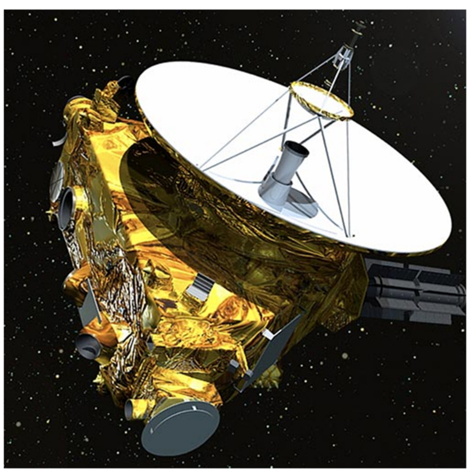
R·I·T

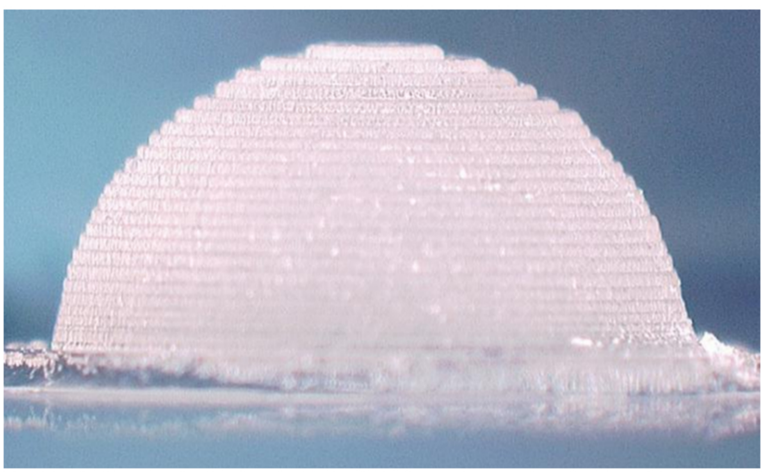
# CENTER FOR DETECTORS

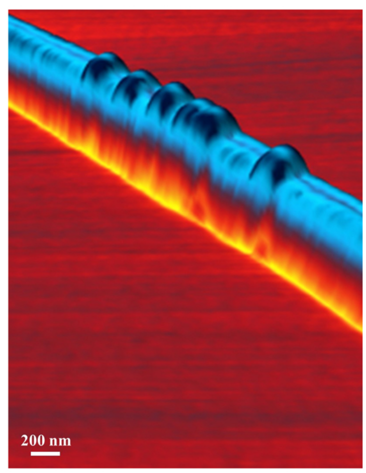
# ANNUAL REPORT 2017











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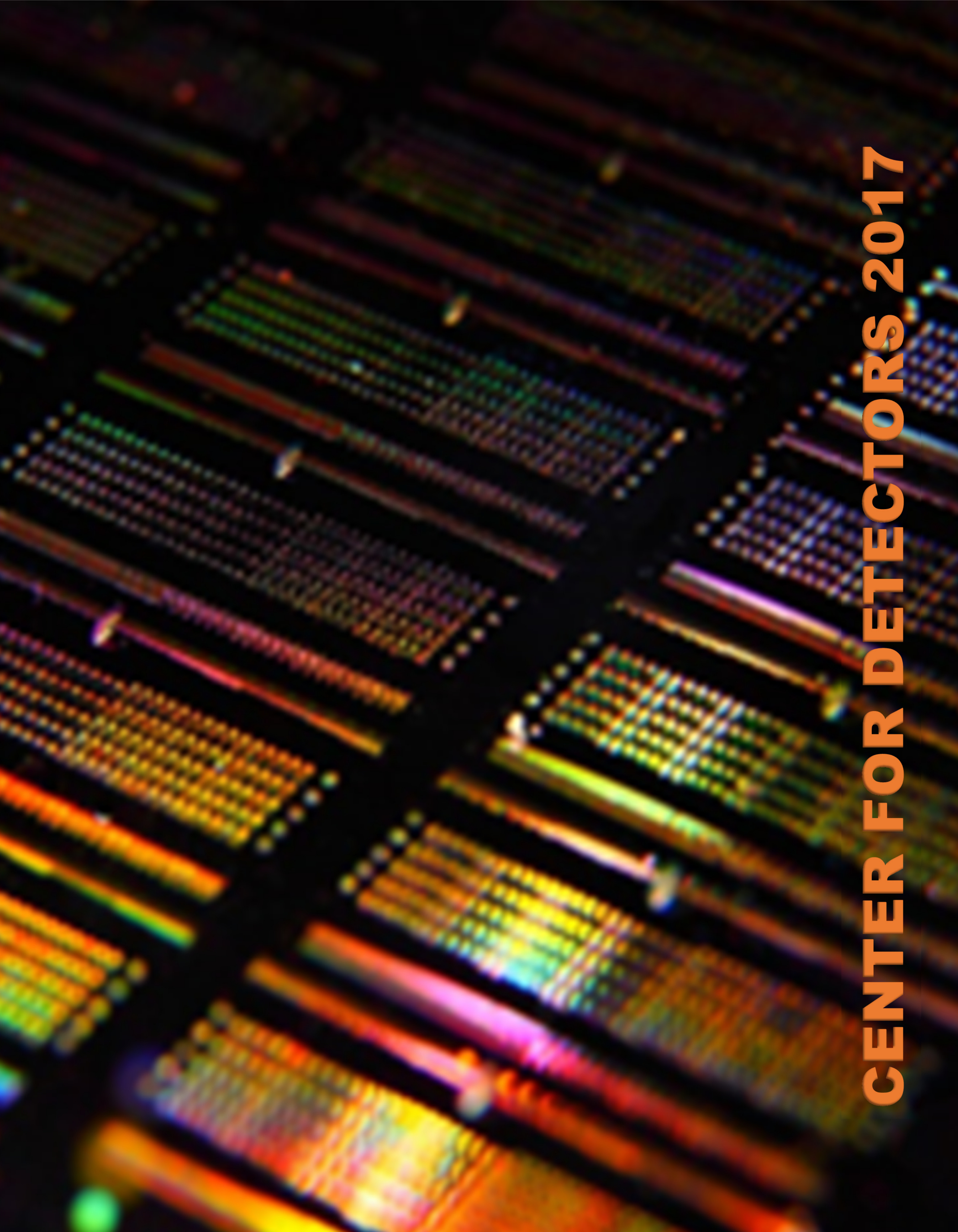

CENTER FOR DETECTORS 2017

# Director's Comments

During the past year, the Center for Detectors (CfD), a Research Center in the Rochester Institute of Technology's College of Science, continued developing new devices for photon detection and transmission. In our seventh year, the CfD led many research developments, including a program to develop a new cryogenic optical camera for steering suborbital rockets. In addition to developing new capabilities, the CfD also led developments to enhance the value of existing assets in space, such as by measuring the pixel response function of NASA's spectacularly successful Kepler planet-finding mission and using NASA's New Horizons spacecraft to measure the faint background light of the Universe.

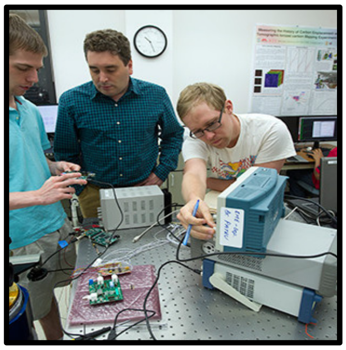
As in previous years, the CfD deeply embedded students from a variety of majors and at all levels of matriculation. Rather than creating special projects for the students, we take the approach of inserting students directly into real-world projects in which their actions have direct and immediate impact. I started this approach as an experiment over ten years ago when I first came to RIT, and I am as impressed today as I was then to see how well the students respond. RIT students, in particular, are eager to participate in CfD research projects because their involvement offers extraordinary real-world learning experiences that will distinguish them in their future careers. As I tell the students when they first start in the CfD, "Check your major at the door – your new major is 'solving problems.'"

Over the past year, the CfD collaborated with other research centers within RIT as a part of the Future Photon Initiative (FPI). This new Signature Interdisciplinary Research Area is the face of photonics for RIT. FPI leverages existing research activities of over 20 professors in pursuit of advancing new photonic devices, such as detectors, integrated silicon photonics, and solar cells. As a way of publicizing FPI, and networking with similar initiatives outside RIT, CfD members attended a number of conferences, including SPIE Photonics West, Optical Fiber Communication Conference and Exhibition (OFC), and Frontiers in Optics (FiO).

This Annual Report, describes the new and exciting activities of the Center of the past year. In it, you will find descriptions of CfD research, education, and outreach programs. I welcome your interest in the CfD and look forward to your support and feedback.

Dr. Donald Figer
Professor, RIT College of Science
Director, Center for Detectors
Director, Future Photon Initiative

# Highlights

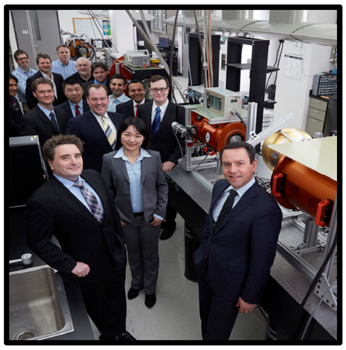


## Research

- CfD research reached the outer Solar System by using data from NASA's New Horizons mission to measure the background light in the Universe. Other projects included New Infrared Detectors for Astrophysics, Development of Digital Micromirror Devices for use in Space, Integrated InAs QD Laser Based Si Photonic Optical Transceiver. For details, and a full list of research, see the Research Project section.

## New Members

- During the past year, the CfD hosted over two dozen new student researchers, in addition to personnel from Precision Optical Transceivers, a company that joined the Future Photon Initiative Industry Partnerships Program. A full list of personnel can be found in the Personnel section of this report.

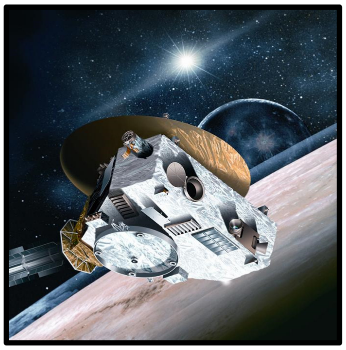


## Future Photon Initiative

- The CfD is an integral part of the Future Photon Initiative, the face of photonics for RIT. As part of FPI efforts, CfD members attended SPIE Photonics West, Frontiers in Optics, OSA, and SPIE Commerical and Sensing conferences. CfD members regularly work with FPI industry partners on collaborative research.

## Publications

- CfD team members published over 40 papers in journals such as The Astrophysical Journal, Nature Communications, and Optical Engineering. In addition, CfD members served as referees for dozens of articles and as expert authors of strategic planning documents for NASA. A full list of publications can be found in the Publications section of this report.



# Executive Summary

This report summarizes activities in the Center for Detectors (CfD) over the past year, spanning July, 2016, through June, 2017. The purpose of the Center is to develop and implement advanced photon devices to enable scientific discovery, national security, and better living. These objectives are met through leveraging multi-disciplinary and symbiotic relationships between its students, staff, faculty, external partners, and by pursuing projects with personnel from multiple colleges, departments, companies, and national laboratories. The CfD was established in January, 2010, as an expansion of the precursor entity, the Rochester Imaging Detector Laboratory. CfD is an Academic Research Center within the College of Science at the Rochester Institute of Technology.



## Research

Over the past year, CfD research consisted of over a dozen projects, funded primarily by federal agencies, such as NSF and NASA. Projects included further technology development, such as new infrared detectors, polarization-detection detectors, and material systems for lasers. In addition to hardware development, researchers used existing technology to determine the natures of stars in the center of the Galaxy and to measure the background light in the Universe.

## Personnel

CfD members come from a wide range of academic programs and occupations. Personnel this year included six professors, two engineers, eight undergraduate research students, 13 PhD students, and other support staff.

## Student Vignettes

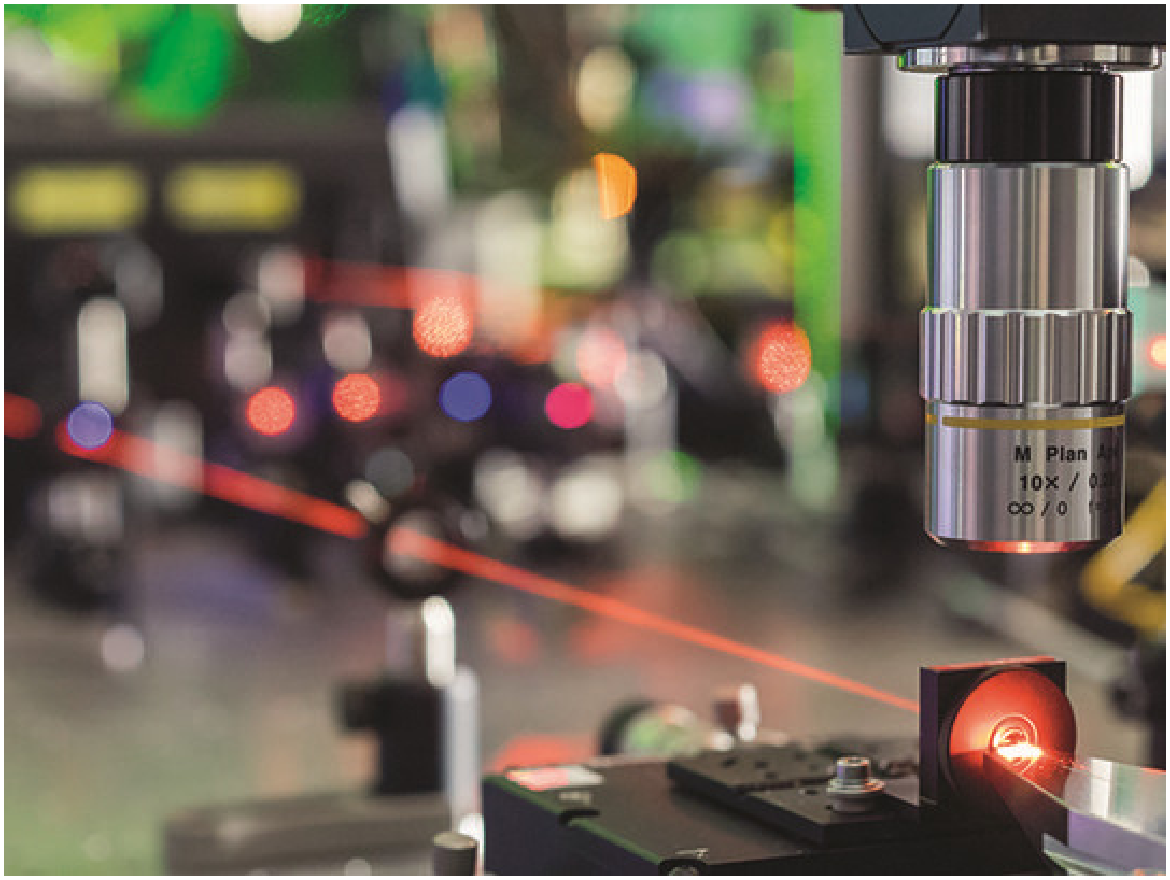
Many of the students do research in the Center's laboratories in support of their academic degree programs. The Center welcomed eight new undergraduate student researchers, while over ten graduate and PhD students continued their research from previous years.

## Publications

CfD researchers published in journals such as, The Astrophysical Journal, Nature Communications, Astronomy and Astrophysics, and Optical Engineering. During this reporting period, CfD researchers published over 40 papers to distinguished publications.

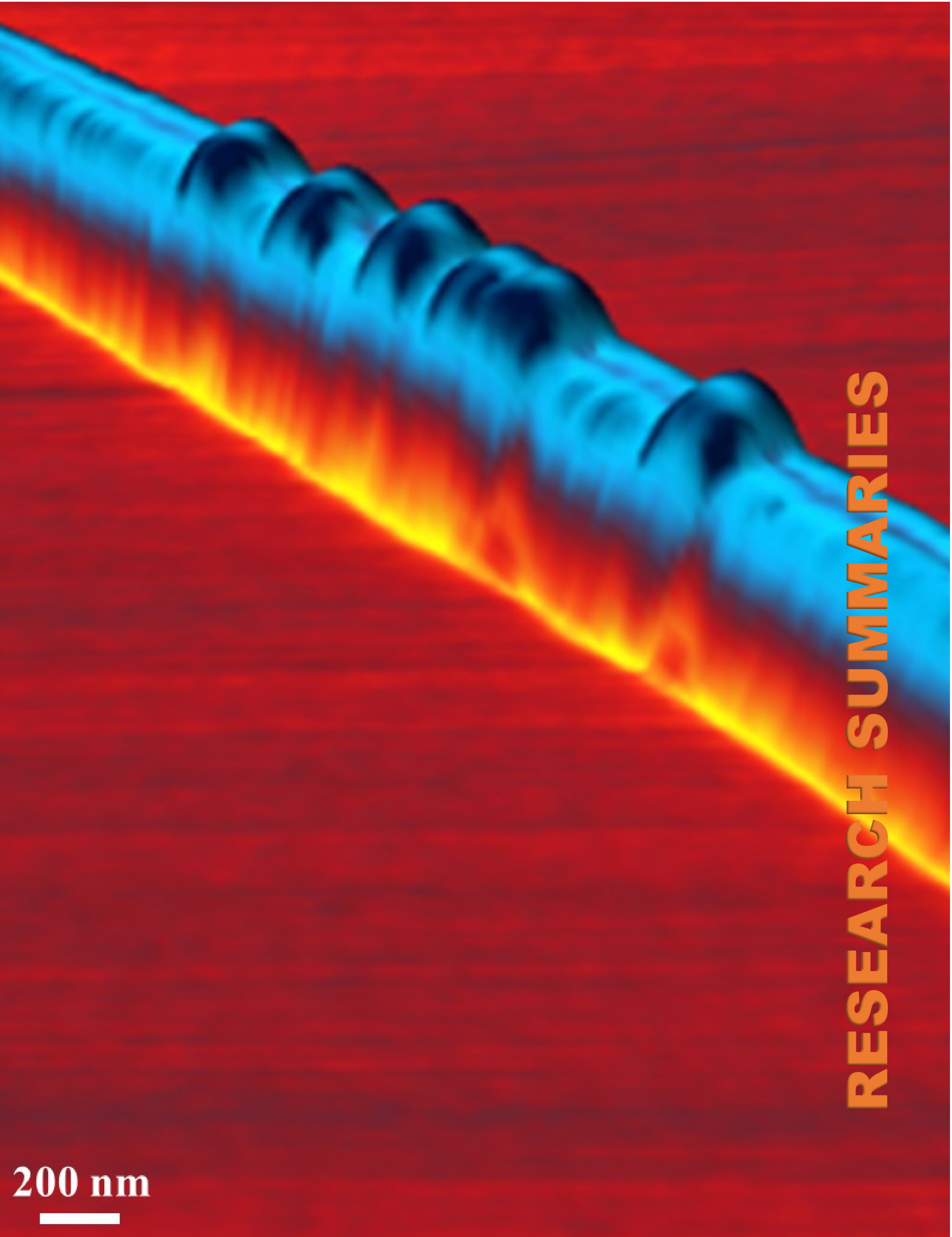
## Equipment and Facilities

The Center for Detectors (CfD) is located in several buildings, with the largest footprint in the RIT IT Collaboratory which has large contiguous spaces for offices and labs, including offices for approximately 20 people, and four research laboratories. The laboratories include the Rochester Imaging Detector Laboratory, an Experimental Cosmology lab, and a nanophotonics lab.




# Research

# RESEARCH SUMMARIES



# Research Projects

## Cosmic Ray Damaged Image Repair (CRDIR)

Private Donations
Donald Figer

High velocity particles in space, known as cosmic rays, strike electronics in an imaging sensor and often create permanent damage. This damage can lead to aberrant pixel values scattered throughout the images obtained with the sensor (see Figure 1). In order to remove the effects of this cosmic ray damage, software can be developed to repair the images. We proposed an algorithm to process the raw data NASA captures from Nikon cameras on the International Space Station in order to remove the effects of cosmic ray damage in a way that is compatible with NASA workflow. A statistical z-score method and a structural convolution method were evaluated against marked images to calculate false positives and false negatives. The convolution method was effective at the 98 percent level, avoiding identifying all stars and other objects of interest in the image and repairing the color filter array data with the local median.

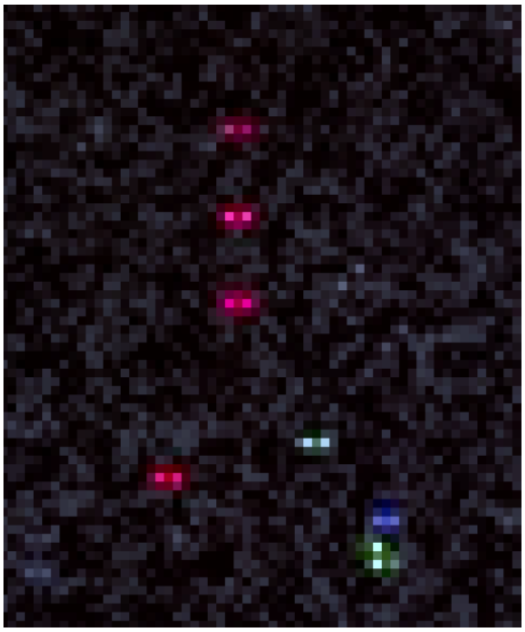


*Figure 1. This is a close-up of an actual image obtained on the NASA International Space Station. One can see aberrant values from damaged pixels distributed in pairs.*

This project was conceived by NASA astronaut, Donald Pettit, RIT alumnus, Peter A Blacksberg (BFA Photo '75), and Center for Detectors (CfD) Director, Don Figer. Donald Pettit is a prolific photographer on the International Space Station (ISS). During a trip to RIT in April of 2015, Mr. Blacksberg visited the CfD to discuss a problem that contaminated pictures taken on the ISS, as related to him by Dr. Pettit. The three principals agreed to form a collaborative project to clean the images of these effects. Several student researchers contributed to the project: Joseph DiPassio (Electrical Engineering), Neil Geurtin (Computational Mathematics and Computer Science), Aravind Warrier (Computer Science), Gilford Fernandes (Computer Science), and Kevin Moser (Imaging Science).

During the past year, Kevin Moser researched the best methods for repairing the images, developed the code for doing so, and wrote a simple graphical user interface that allows a user to repair all the images in a chosen folder. Both correction methods performed reasonably well in identifying bad pixels, but the z-score method suffers from a relatively high rate of false positives, especially in cases where there are sharp features in the image, such as stars and detail in the space station itself. Figure 2 captures the situation quite well. One can see that bad pixels (which usually appear in pairs) have been removed, but also that the bright star seems to have been affected. Apparently, the z-score algorithm incorrectly identified some of the pixels covering the bright star as aberrant in the red and blue channels. After modifying the values of pixels in those channels, the star now appears to be green.

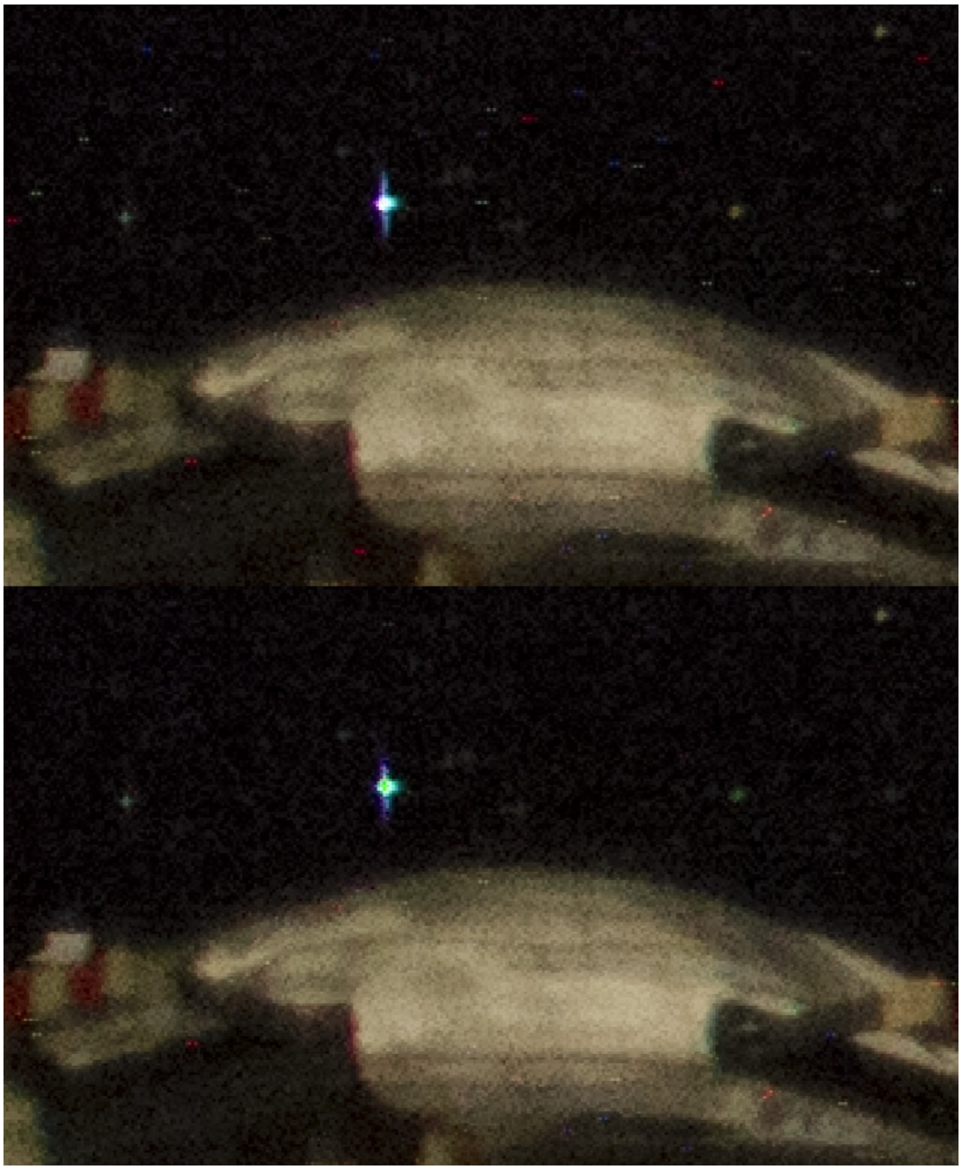


*Figure 2. These images show the effectiveness of the z-score algorithm. The image shows a field of stars and detail of the space station near the bottom of the image. The top is pre-corrected, and the bottom is post-corrected.*

The structure convolution method produced better results (see Figure 3). This method takes advantage of the fact that the aberrant values appear to be arranged in pairs. It is not clear why cosmic rays should damage two pixels at the same time. It was not possible to access the raw pixel data before on-board processing, so it was not possible to further explore the cause of this effect.

In addition to the work to develop the best correction algorithm, Mr. Moser also developed a graphical user interface that a user at NASA could use to correct a large number of images in a batch mode. Further work will include enhancements of the algorithm, inclusion of more options for the user interface, and provisions to optimize the parallel processing of images.

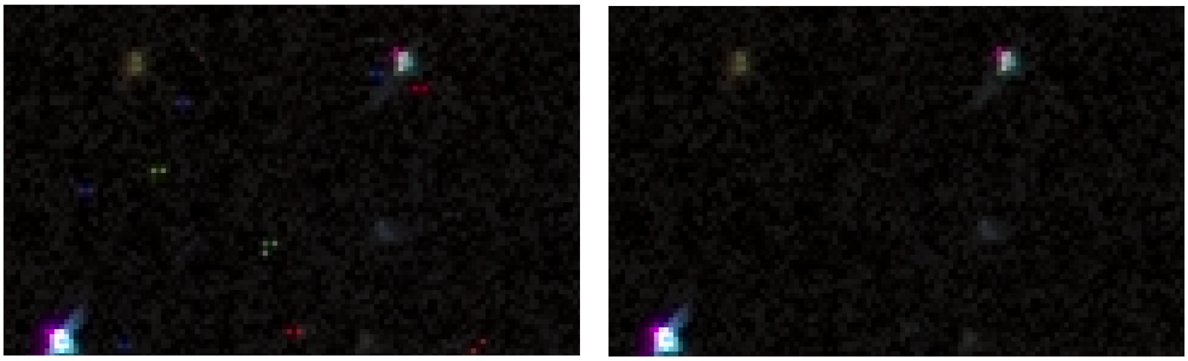


Figure 3. These images show the effectiveness of the convolution algorithm. The left is pre-corrected, and the right is post-corrected.

## Cosmology with the SPHEREx All-Sky Spectral Survey

NASA/JPL
Michael Zemcov



SPHEREx (Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer) is a proposed all-sky spectroscopic survey satellite (see Figure 4) designed to address all three science goals in NASA's Astrophysics Division: probe the origin and destiny of our Universe; explore whether planets around other stars could harbor life; and explore the origin and evolution of galaxies. SPHEREx will scan a series of filters systematically across the entire sky. The SPHEREx data set will contain R=40 spectra $0.75< \lambda <4.1$ μm and R=150 spectra for $4.1< \lambda <4.8$ μm for every 6.2 arcsecond pixel over the entire-sky. Over the past year, our team has been involved in the NASA Phase A review and selection process for the SMEX-class mission opportunity, which included submission of a greater than 300 page concept study report, site visits, and various assessments and reviews. In early 2017, NASA announced the result of the SMEX program selection process, where SPHEREx was not selected for Phase B. SPHEREx has been re-proposed to the NASA MIDEX program, and we expect to hear the selections for Phase A of that program in mid-2017.

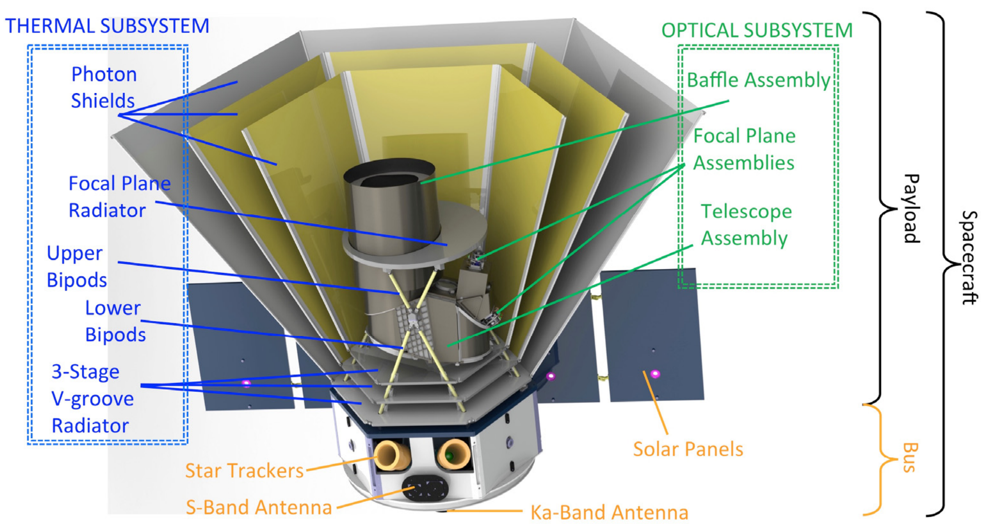



Figure 4. This image shows the main components of the SPHEREx spacecraft.

## THz Modeling and Testing

NYSTAR/UR-CEIS/Harris
Zoran Ninkov

A group consisting of Harris engineers, RIT scientists, University of Rochester engineers and scientists designed and manufactured a room temperature silicon Complementary metal–oxide–semiconductor (CMOS) imager for terahertz (THz) frequencies using metal-oxide semiconductor field effect transistors (MOSFETs). THz frequencies have been largely unexplored due to high absorption within water, however there has been an increase in interest with the rise in high-altitude and space-based telescopes. Emission lines in spectra within the THz regime exhibit cool molecular gas which traces protoplanetary disks and star formation rates within galaxies. This technology also has other applications within the medical and security fields because of the nonionizing, non-harmful nature of THz radiation.

For pixel optimization, chips with single pixels utilizing varying design dimensions (*i.e.*, different antennas, gate widths, et cetera) were designed. Creating an asymmetrical design within the FETs, making the source longer than the drain and connecting the antenna petals to the gate and source, increases the THz response. The CfD group has developed a testing method for the single pixel characterization. A custom low noise enclosure and cabling setup was constructed to run the FETs under various biasing conditions measuring voltage and current to determine the I-V characteristics, transconductance, threshold voltage, and THz responsivity. The primary radiation source is a tunable THz source (0.18 to 0.25 THz) used with a TPX lens to collimate the beam onto the chip. There are two chips (Figure 5) currently being tested for a total of over 40 varied test structures. By parametrically testing the structures, the optimal pixel design will be found for future imager designs. The advantage of this technology is that it will be cheaper than other THz technologies to manufacture and it does not have to be cooled to extremely low temperatures. This project's goal is to advance knowledge of the detection mechanism and lead to the creation of an integrated imaging system, which can be used for many different applications.



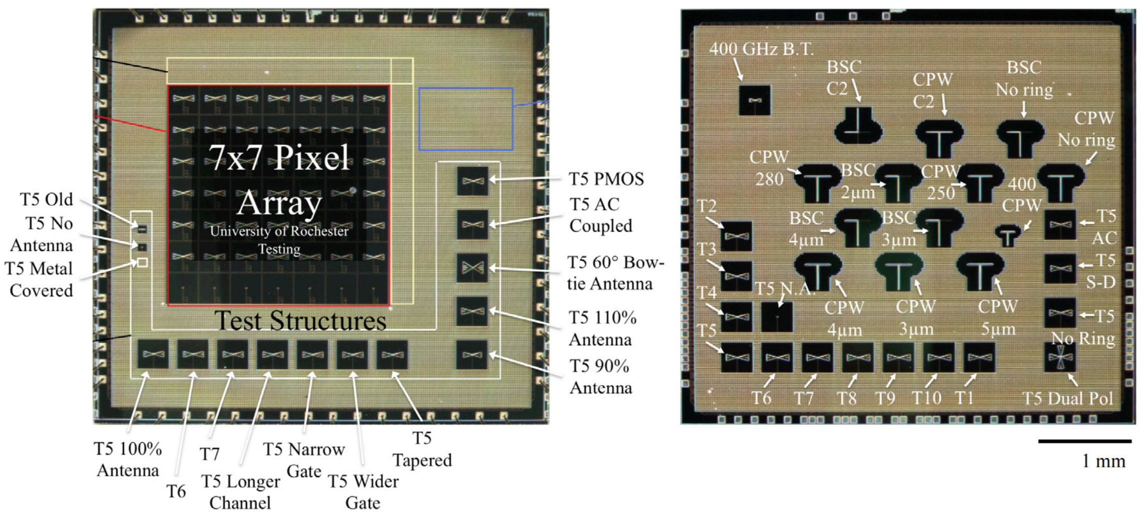



*Figure 5. The two THz chips currently being tested at RIT are shown with the individual test structures labeled on each chip*

## Enhancing the UV/VUV sensitivity of CMOS Image Sensors

NYSTAR/UR-CEIS/Thermo Fisher Scientific
Zoran Ninkov

Charge-coupled devices (CCDs) and CMOS arrays have limitations in spectral sensitivity as delivered from the foundry. The front-side gate structure of a CCD is absorptive at ultraviolet (UV) wavelengths. For high efficiency, CCDs are back illuminated, which is expensive to do, and unfortunately the Si substrate is highly reflective. Additionally, UV photons have a very short absorption length in silicon. The electron–hole pairs produced by the photon interaction are trapped at the back surface and therefore never reach the accumulation phase gate. These issues have resulted in difficulty in producing efficient CCD-based UV/Far UV (FUV) detectors. Delta doped back illuminated CCDs are the best solution to this problem. Anti-reflection (AR) coating the CCD is difficult in this spectral region as the coatings available only provide improvement over a narrow spectral region. This is especially concerning for application in UV/FUV spectroscopy where a wide spectral range needs to be recorded simultaneously (e.g., in UV plasma spectroscopy).

Charge Injection Devices (CIDs) are an alternative to CCDs and photodiode based CMOS imagers. The CID is monolithic MOS silicon charge transfer device with extremely high dynamic range that is remarkably resistant to gamma rays and neutrons that is now being tested with a deployment to the ISS.[1]

Historically, CCDs have been coated with an organic phosphor, lumogen, to convert UV photons to visible light that can be detected in the CCD or CMOS detector array. Issues with lumogen have included; the broad spectrum of the fluorescent light, degradation with time, as well as UV and vacuum exposure, uniformity problems and pinhole development. Quantum dots offer an alternative "phosphor." Quantum dots (QD) are small (typically 2-10 nm) semiconductor crystals whose size in all three dimensions is on the order of the exciton Bohr radius. The physical size of the quantum dot determines its fluorescent wavelength when excited by UV light. A QD coating will resist pinhole formation, as QDs are large compared to an organic molecule. As QDs are inorganic crystals, chemical bond changes require sufficient additional energy for atomic displacement into an interstitial lattice location. Thus, QDs should resist photo-bleaching and radiation damage.

This work investigates a process to deposit a fluorescent quantum dot film on a silicon detector array (i.e., a CID) to down-convert high-energy photons to a wavelength at which the detector array is sensitive. This concept is illustrated in Figure 6 (left). The composition and thickness of the quantum dot layer may be altered during deposition to tune the wavelength of peak fluorescence to the wavelength of peak quantum efficiency of the detector array. The absorption cross section of quantum dots in the UV requires thickness of quantum dots of <200 nm for complete absorption of incident deep UV radiation. An Optomec Aerosol Jet Rapid Prototyping (AJP) System permits precisely controlled deposition of aerosolized inks. The quantum dots used are available commercially from Ocean Nanotech. Specifically, they are QSP-540 quantum dots of CdSe/ZnS Core/Shell with a peak fluorescence at 540 nm. An SEM image of a QD deposition reveals spherical features, of about a micron in diameter, that seem to be agglomerates of multiple 10 nm sized QD that have been formed during the aerosol generation phase of printing. These droplets appear to further agglomerate upon other agglomerates (Figure 6, right).

[1] Batcheldor, D., and Ninkov, Z. 2017, see http://www.iss-casis.org/NewsEvents/OnStation/tabid/113/ArticleID/247/ArtMID/570/US-National-Laboratory-Research-Payloads-Set-for-Launch-on-SpaceX-CRS-10.aspx

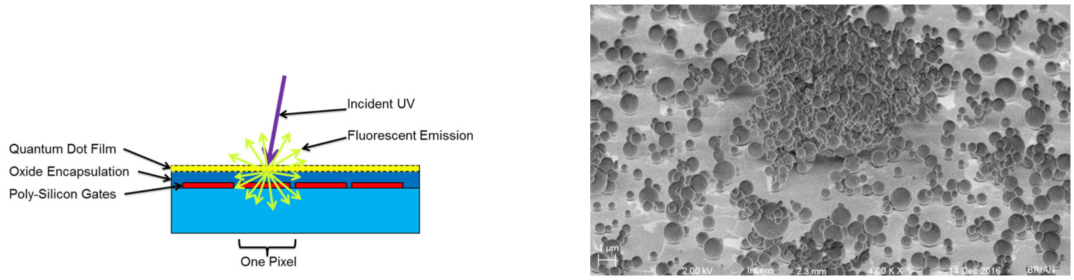



*Figure 6. The two THz chips currently being tested at RIT are shown with the individual test structures labeled on each chip*

## Imaging Polarimetry with Microgrid Polarizers

Moxtek, Inc.
Zoran Ninkov

Polarization is an intrinsic property of light, like frequency or coherence. Humans have long benefited from our ability to distinguish light of different frequency based on its color. However, our eyes are not sensitive to the polarization of light. Devices to measure polarization are relatively rare and expertise in polarimetry even more so. Polarization sensors based on micropolarizer arrays appear to be the first devices capable of bringing polarimetric capability to a wide range of applications. Whereas previous polarimeters were built to perform very specific measurements, the same micropolarizer-based camera can be used on a telescope, a microscope, or with a conventional camera lens.

At RIT, we investigate the operating principles of micropolarizer arrays using high resolution 3D simulations and develop strategies to fabricate and characterize micropolarizer-based imaging polarimeters. Furthermore, we created software tools to produce synthetic observations of various scenes. These synthetic data are a powerful tool to study the many effects that can give rise to systematic and/or random errors during the data analysis process. Using the RIT Polarization Imaging Camera (Figure 7), we are able to achieve a polarimetric accuracy of ~0.3% in images of extended objects and unresolved sources.


*Figure 7. The RIT Polarization Imaging Camera is a compact, snapshot, imaging polarimeter, suitable for use with a wide range of imaging systems, from telescopes to microscopes. Here, RITPIC is shown with a f/0.95 photographic lens.*

Recently, we deployed RITPIC on the 0.9 m SMARTS telescope at the Cerro Tololo Inter-American Observatory near La Serena, Chile (Figure 8, top). Jupiter was one of the many objects that we observed during this run, and its polarization structure is shown in Figure 8 (bottom). The strong polarization near the poles of Jupiter is clearly seen in our maps, as well as the more subtle structure across Jupiter's disk.

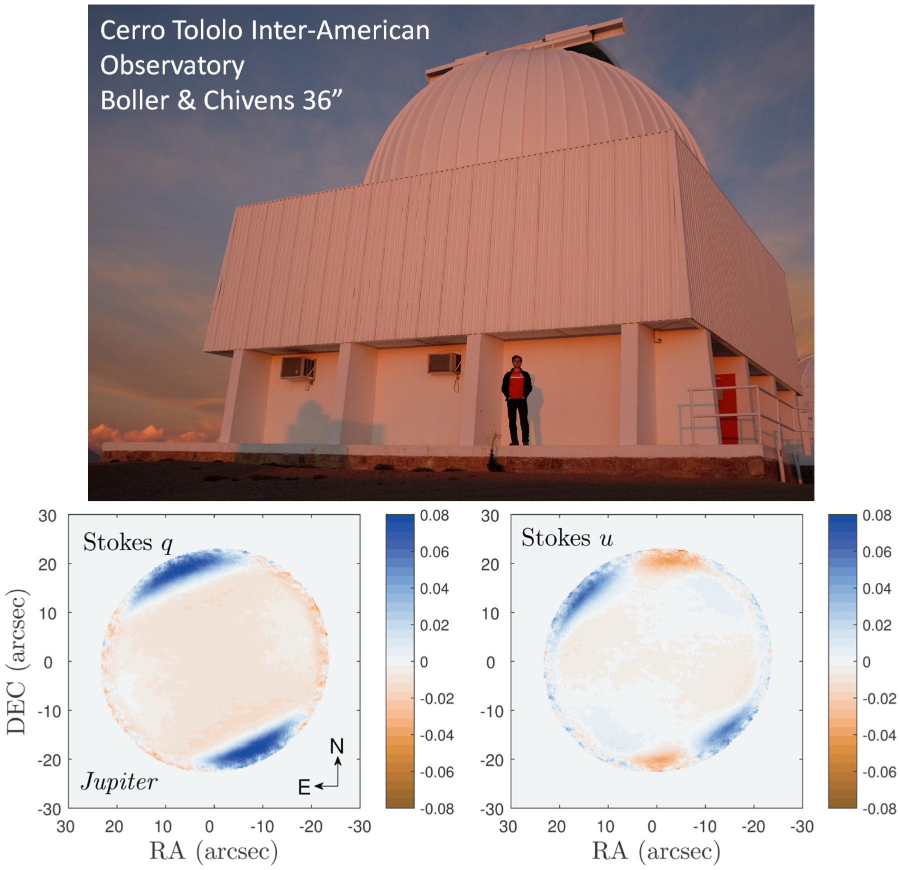


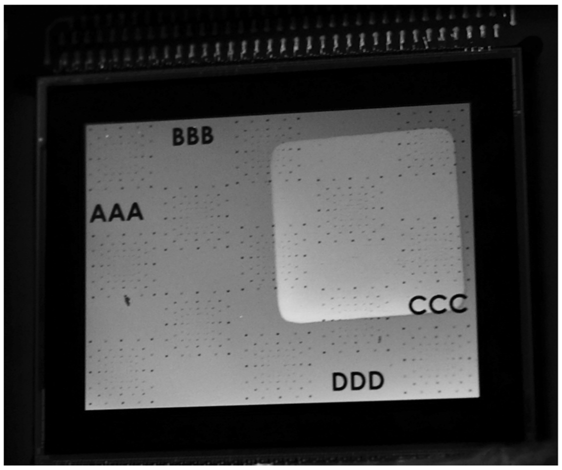

*Figure 8. (top) RITPIC was deployed for its commissioning run on the 0.9 m telescope at CTIO by Dmitry Vorobiev. (bottom) The polarization at the poles and across the face of Jupiter exhibits complex structure. These maps are a key probe of atmospheric composition of solar system planets, and can even offer clues to the atmospheric structure of extra-solar planets.*

## The Development of Digital Micromirror Devices for use in Space

NASA
Zoran Ninkov

This project is developing a commercially-available Digital Micromirror Device (DMD) with an ultraviolet transparent window suitable for use in a multi-object spectrograph (MOS) in a future NASA Explorer Mission (Figure 9). A large spectroscopic survey requires a MOS capable of recording the spectra of hundreds of galaxies in a single exposure. The MOS must have adjustable slits to eliminate confusion with nearby sources and to block out unwanted zodiacal background, which would otherwise swamp the light from these faint galaxies. The MOS should have access to the far-ultraviolet (120-200 nm) radiation emitted by a z~1 galaxy because this spectral region has a rich set of diagnostics of stars, gas, and dust in the galaxy. Access to the blue-red spectral regions (200-800 nm) is also essential for determining the precise redshift of a galaxy, its stellar mass, abundances of the elements, and for characterizing dust extinction. Because the light from a z~1 galaxy is redshifted before reaching us, a large spectroscopic survey should be sensitive over the spectral interval, 200-1600 nm.

Recently, CfD researchers and our collaborators at NASA GSFC successfully re-coated a section of a DMD with high purity aluminum, to improve its UV reflectance. The UV reflectance of the DMD (ignoring losses due to fill factor and diffraction) is less than that of pure aluminum, because the DMD mirrors are made with an aluminum alloy. At a wavelength around 200 nm, the DMD reflectance drops rapidly (Figure 9). This decrease is seen for all aluminum (and aluminum-alloy) mirrors, if they are not protected against the formation of an aluminum oxide layer. The re-coated DMD remained operational, with no obvious cosmetic differences between the coated and original regions, except improved reflectance. The re-coated region showed a reflectance improvement of several percent across the visible range, with more significant gains in the UV; at 200 nm, the reflectance increased from 48% to 65%. At this wavelength, the reflectance difference between the re-coated DMD and a standard aluminum mirror is due to the 92% fill-factor of the DMD. At longer wavelengths, diffraction creates additional losses, as well as the ``ringing'' seen in the blue curve.



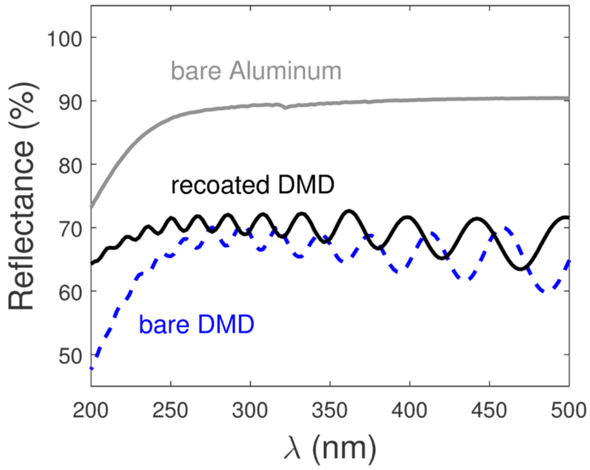




*Figure 9. (left) We re-coated a section of a TI XGA DMD with high purity aluminum at NASA GSFC (square in upper right). The DMD remained operational after the coating process. (right) The reflectance of the re-coated region increased across the visible range, with significant improvements in the UV.*

Neither the re-coated DMD nor the witness mirror sample was protected against oxidation in this experiment, so the reflectance drop off near 200 nm persists. However, our initial tests show that DMDs can survive this type of re-coating, suggesting that DMDs can be made usable in the 100 nm – 400 nm range if the coating is protected with a fluoride film. Lithium fluoride windows can be used to protect the DMD using the re-windowing techniques we developed as part of this Strategic Astrophysics Technology program, to allow the operation in the range of 108 nm – 3000 nm. Furthermore, we are investigating the use of DMDs without protective windows, to extend the usable range to 91.2 nm (rest frame Lyman limit), which is near the current state-of-the-art aluminum coatings.

## New Infrared Detectors for Astrophysics

NSF/NASA
Donald Figer

This project extends the work done in the Phase I project to develop new detectors that use HgCdTe deposited on silicon substrates. The key objective of this phase is to provide the ground-based astronomy community with a new family of detectors that have very large formats, low cost, and state-of-the-art performance.

Planned project tasks during the past year consisted of HgCdTe/Si wafer fabrication, detector/readout integrated circuit (ROIC) hybridization, packaging, and detector testing. Three substrate-removed HgCdTe/Si detectors were processed through this full sequence of tasks. Different substrate removal techniques and annealing processes were used for the devices in order to compare the effects of these processes when compared to devices processed using older recipes. The intent of this comparison was to develop the best recipes for the next fabrication lot to be completed during the next year. Additionally, one device was characterized before and after being thinned to compare detector performance metrics after substrate removal to those observed before removal.

These tasks are essential to the project and were directly funded by the budget. In addition to the standard characterization tests, exhaustive measurements of persistence were performed as part of an investigation to determine if new processing steps could reduce high persistence previously measured. A summary of progress, with completed milestones, is given in Figure 10.

| Milestone | Status | Comments |
|---|---|---|
| Design/Peer Review proposed changes from previous projects | Complete | |
| SB301 ROIC for read noise evaluation | Complete | Two 1K x 1K SB301 ROICs tested |
| Up to two 1K x 1K 2.5 µm for image persistence evaluation | Complete | Two 1K x 1K 2.5 µm devices delivered and tested |
| Up to four 1K x 1K 2.5 µm substrate removed device from Lot 1 | Complete | Three substrate removed devices delivered and tested |
| Up to four 1K x 1K 2.5 µm substrate removed device from Lot 2 | Incomplete | |

*Figure 10. The table summarizes progress in completing project milestones.*

The main objective for this round of fabrication was to address the high persistence and dark current tail found in the previous lot. Based on the characterization results from the previous fabrication run, we determined that the devices from the previous lot suffered from short carrier lifetime and high bulk generation recombination currents. We hypothesized that this was due to a high number of coupled dislocations, so the goal in this fabrication run was to reduce the number of dislocations.

Threading dislocations occur due to the mismatch between the lattice constants of the HgCdTe and the Si substrate. Some of these locations cluster and form coupled dislocations. These coupled dislocations produce the observed high dark current. Thus, reducing dislocations is crucial to reducing the dark current. The edge pit density (EPD) is a useful measurement of the number of threading dislocations. Since reducing the number of coupled dislocations matters the most, even a moderate improvement in EPD should result in great improvement in the dark current, as decreasing dislocations by ~N should result in a decrease in coupled dislocations by ~N2.

Raytheon produced two wafers with buffer layers that are twice as thick as those used in the last fabrication lot. The thicker buffer layer reduced the EPD significantly in this fabrication lot compared to the previous fabrication lot (see Figure 11), and it was expected to reduce the large tails seen in the distributions of the dark current in individual pixels in the previous fabrication run.

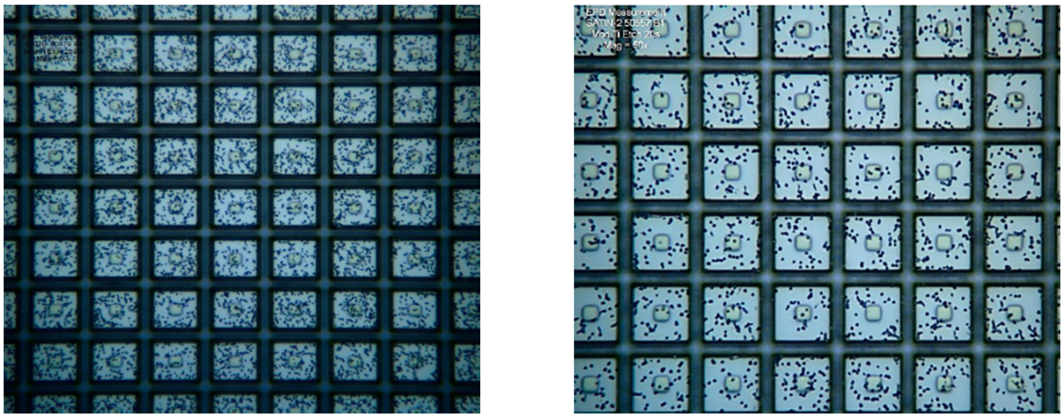


*Figure 11. Threading dislocations, the dots in each pixel, are shown for wafers from the previous fabrication run (left) and this fabrication run (right). EPD is much smaller in this fabrication run, at ~1.5($10^7$) $cm^{-2}$, than in the previous fabrication run, at ~4($10^7$) $cm^{-2}$.*



In addition to the thicker buffer layers, four combinations of annealing and substrate removal processes were applied to the two wafers to study the effects of different processes on the dark current and other performance metrics, leading to an optimization of the annealing and substrate removal processes for maximum performance gains. The two wafers were subjected to different annealing processes, the nominal annealing process, called SATIN, and an alternative process developed to reduce the dark current for a separate NASA short-wave infrared (SWIR) astronomy project. Two sensors from each wafer were, in turn, subjected to two different substrate removal processes, a baseline process and an alternative process. Four different combinations of annealing and substrate removal processes were applied to the four detectors produced in this fabrication lot, as summarized in Figure 12.

| SCA | Wafer | Substrate Removal |
|---|---|---|
| F10 | 557 (alternative anneal) | Baseline Process |
| F11 | 559 (Satin anneal) | Baseline Process |
| F12 | 557 (alternative anneal) | Alternative Process |
| F13 | 559 (Satin anneal) | Alternative Process |

*Figure 12. The table shows a summary of fabrication processes applied to each detector.*

The alternative substrate removal process is potentially relevant because it significantly reduced dark current in another project, albeit one that did not use HgCdTe/Si. Three of the four detectors produced, F10, F12, and F13, were delivered to RIT for characterization. F13 was specially earmarked for characterization before and after substrate removal in order to study the change in detector performance metrics after the substrate removal. Changes in performance were closely monitored as there were observations in the past in which the crosstalk between pixels increased after substrate removal. F10 and F12, in contrast, were only characterized after being thinned. F11, the remaining device out of the four, failed due to a bad ROIC (ReadOut Integrated Circuit) during the hybridization and packaging steps; hence it was not characterized at RIT.

As high persistence and dark current were identified in the previous fabrication run as deficiencies, these characteristics were examined thoroughly in parts from this fabrication run. Detectors from the previous lot had low persistence for fluences below the full well, but once the detectors were flood illuminated above the full well, the persistence exhibited a discrete jump in which the persistence increased by an order of magnitude compared to the persistence for fluences below the full well.

As there have been reports of an increase in crosstalk in HgCdTe (and other materials) devices after the substrate is removed, the crosstalk on F13 was measured, pre- and post-thinning, to confirm findings from other groups. The increase in crosstalk likely stems from backfilling the device with epoxy, a step that is often used in order to increase the mechanical integrity of the device. The epoxy has a relatively high dielectric constant, therefore increasing the interpixel capacitance.

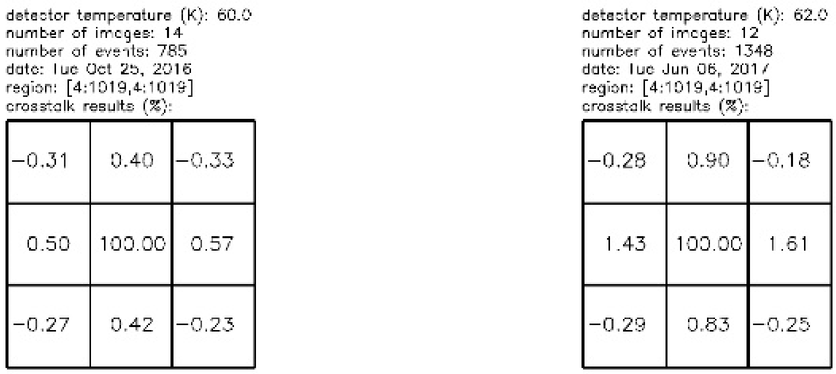



*Figure 13. The crosstalk on F13, before (left) and after the substrate removal (right), is shown.*



The pre- and post-thinning crosstalk measurements are shown in Figure 13. The crosstalk did indeed increase about two- to threefold after the substrate removal. The crosstalk on F10 and F12, which are also thinned, have similar crosstalk results, proving that the increase in the crosstalk on F13 after the substrate removal is not an isolated incident. Based on these findings, Raytheon is exploring an option to switch to a softer epoxy that will perform better in crosstalk. The softer epoxy has the added bonus of imposing less stress on the lattices, which should result in lower dark current.

## Integrated Quantum Photonics for Photon-Ion Entanglement

Air Force Research Laboratory
Stefan Preble

The primary objective of this project is the realization of an integrated photonics platform compatible with photon-ion entanglement. The platform will consist of photon sources and entangling circuits that interface with the visible/UV wavelengths of ion (such as Yb+, Ca+, Be+, Mg+, Sr+, Ba+, Zn+, Hg+ and Cd+) transitions. The challenge with realizing such a platform is that integrated photonic chips are not well developed at visible wavelengths because of the traditional focus on telecom wavelength compatibility. We are developing a platform that does operate at short wavelengths by using Aluminum Nitride (AlN), which is a large bandgap semiconductor that is transparent to the deep-UV (see Figure 14). In parallel, we are leveraging our successes in quantum integrated photonics in telecom-compatible platforms, particularly silicon photonics. This will allow rapid validation of high performance photon sources, entanglement circuits and quantum sensors. These circuits will then be transitioned to the new visible/UV platform, or interfaced with ions directly by using frequency conversion.

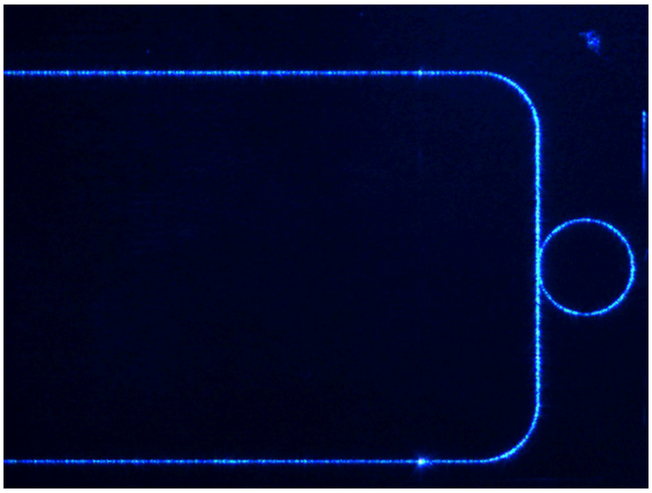


*Figure 14. The image shows visible light propagating in an aluminum nitride waveguide and ring resonator.*



## Quantum optical resonators: a building block for quantum computing and sensing systems

National Science Foundation
Stefan Preble

The overall goal of this project is to experimentally demonstrate the quantum optical response of ring resonators and use them as a robust building block for quantum information processing. We have shown that ring resonators operating in the quantum regime exhibit a resonant response that depends on the photon state. Unlike beam splitters, which operate with maximum fidelity with only one set of parameters, the unique passive feedback in ring resonators ensures high fidelity quantum interference over effectively an infinite device parameter space. The devices compact size and ability to be reconfigured dynamically with low energy requirements ensures that ring resonators are the ideal building block for realizing complex quantum optical circuits (Figure 15).

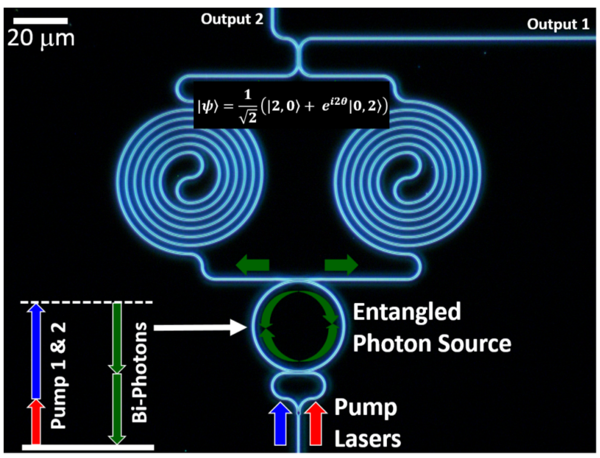



*Figure 15. The picture shows a dark-field microscope image of a quantum circuit on the Silicon-On-Insulator chip consisting of an integrated pump splitting circuit, ring resonator (Q~15 k, FSR~5 nm) entangled bi-photon source and Mach-Zehnder analysis circuit. This circuit generates a two-photon path entangled quantum state.*

## High Performance Integrated InAs Quantum Dot Laser Based Si Photonics Optical Transceiver

NSF
Stefan Preble

The project is focused on the realization of high performance optical transceivers integrated onto a silicon chip using robust InAs quantum dot lasers. Specifically, this project will overcome one of the largest challenges in silicon photonics, which is the seamless integration of *robust and low-powered* lasers with other silicon photonics devices, where the lasers need to operate at relatively high ambient temperatures (70-80°C) and the emission wavelengths need to be varied to achieve a multichannel laser array with large transmission bandwidth. Our approach is to bond III-V heterostructures that contain quantum dots onto silicon substrates. Quantum dots (QD) possess 3D confinement and delta-function like density-of-states (DOS), and as a result, and unlike their quantum well counterparts, have good temperature stability, low power consumption, high differential gain, and zero chirp and α-factor. In addition, they are spectrally broad due to large size distribution of the quantum dots, and as a result can be used to realize broadband laser sources. Furthermore, in order to realize high gain, and as a result low threshold power, we are uniquely aiming to directly integrate the lasers to waveguides through a butt-joint waveguide coupling scheme, as seen in Figure 16. This will enable all of the transceiver components to be integrated into the same plane, significantly increasing performance and decreasing the overall footprint – in turn, allowing denser integration for overall higher bandwidth at lower powers.



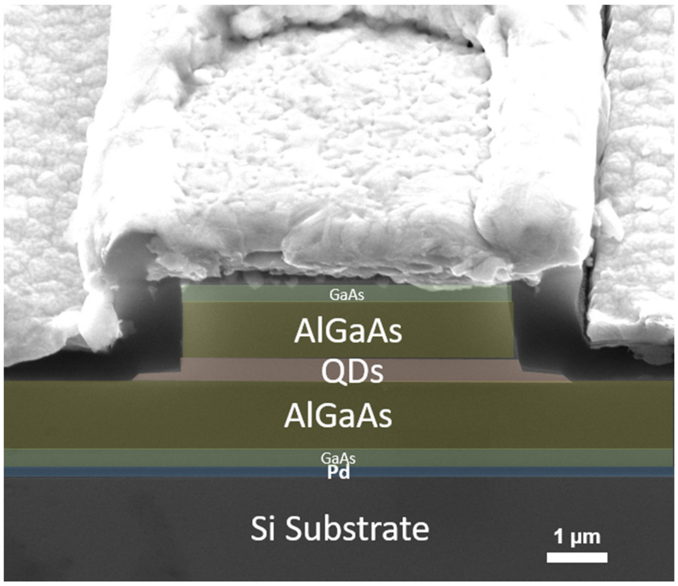



*Figure 16. The image above shows the scanning electron microscope of a quantum dot laser on Silicon.*

## Multi-Color Anisotropy Measurements of Cosmic Near-Infrared Extragalactic Background Light with CIBER2

NASA/Caltech
Michael Zemcov

The Cosmic Infrared Background ExpeRiment (CIBER-2) is a near-infrared rocket-borne instrument designed to conduct comprehensive multi-band measurements of extragalactic background light anisotropy on arcsecond to degree angular scales. Recent measurements of the near-infrared

Extragalactic Background Light (EBL) anisotropy find excess spatial power above the level predicted by known galaxy populations at large angular scales. CIBER-2 is designed to make measurements of the EBL anisotropy with the sensitivity, spectral range, and spectral resolution required to disentangle the contributions to the EBL from various sources throughout cosmic history. CIBER-2 consists of a 28.5 cm Cassegrain telescope assembly, imaging optics, and cryogenics mounted aboard a sounding rocket. Two dichroic beam-splitters spectrally subdivide the incident radiation into three optical paths, which are further subdivided in two wavelength bands per path, for a total of six observational wavelength bands that span the optical to the near-infrared and produce six 1.2 by 2.4 degree images recorded by three 2048×2048 HAWAII-2RG detector arrays. A small portion of each detector is also dedicated to absolute spectrophotometric imaging provided by a linear-variable filter. The instrument has several novel cryogenic mechanisms, a cryogenically-cooled pop-up baffle that extends during observations to provide radiative shielding and an electromagnetic cold shutter. Over the past year, our local team has been contributing to the international collaboration by assisting with: overall instrument design, including mechanical and electronic systems; integrating the instrument; and flight planning activities. In addition, the RIT team is responsible for delivering the cryogenic star tracking camera system, which is currently in the final design and preliminary fabrication phase.



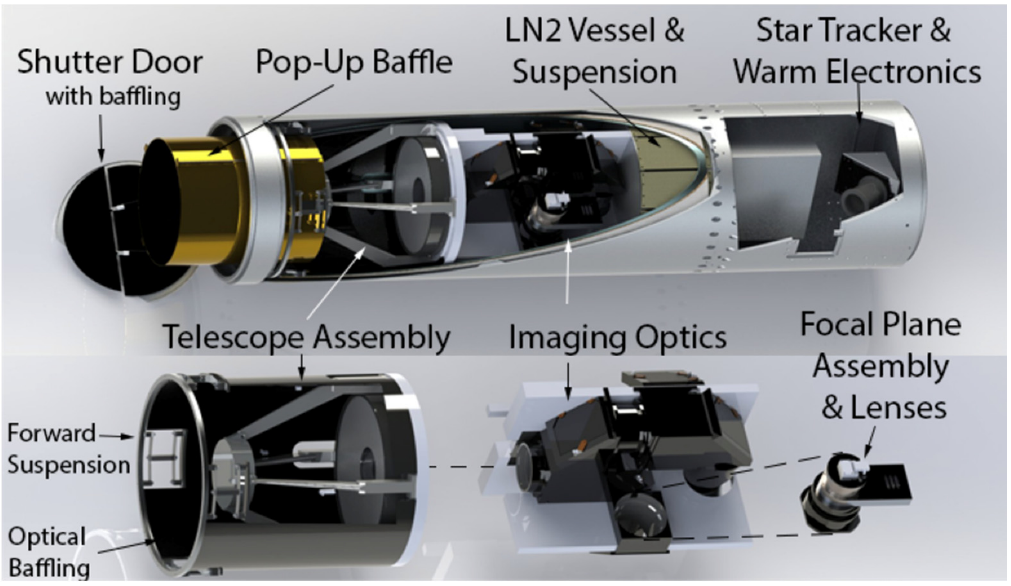



*Figure 17. This is a cross-sectional view of the CIBER2 experiment.*

## Quantum Silicon Photonics Measurement System

Air Force Office of Scientific Research (AFOSR)
Stefan Preble

The primary objective of this DURIP (Defense University Research Instrumentation Program) project is to demonstrate quantum photonic circuits on a Silicon chip by using a quantum photonic measurement system with ultra-low noise and high efficiency. Quantum information science has shown that quantum effects can dramatically improve the performance of communication, computational and measurement systems. However, complex quantum systems have remained elusive due to the large number of resources (photon sources, circuits and detectors) that need to be tightly integrated. Professor Preble is realizing breakthroughs by integrating quantum circuits on a silicon chip and developing scalable building blocks based on ring resonators, which dramatically reduce the footprint of the circuits and enable novel functionalities. The quantum measurement system, consisting of a low-noise tunable laser and high efficiency single photon detectors, is a critical enabler of these Quantum Silicon Photonic chips.

## Integrated Photonics Education at RIT

### Empire State Development/Research Foundation of SUNY
### Stefan Preble

The objective of this project is to support AIM Academy (the education arm of AIM Photonics) by providing education modules for integrated photonics design, manufacturing, packaging and testing. This activity directly benefits the future workforce that will enable the silicon photonics economy.

We will also work to educate students, workforce, veterans and the community with: short courses, degree courses, establish an integrated photonics practice facility, assess workforce needs and develop an ME degree in Integrated Photonics Manufacturing in collaboration with MIT. Figure 18 shows students who are involved in laboratory research that advances silicon photonics.

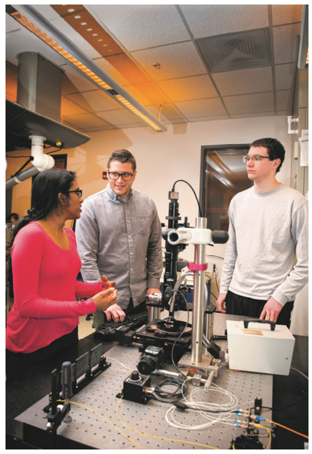


*Figure 18. Students measure an integrated photonic wafer manufactured in RIT's SMFL, from left-to-right, Sanjna Lakshminarayanamurthy (Teaching Assistant), Tayler Swanson, Thomas Kilmer.*

## Understanding and Engineering Valence Band Structures of III-Nitride Semiconductors for High-Efficiency Ultraviolet Lasers and Emitters

### Office of Naval Research
### Jing Zhang

The purpose of this research is to develop solutions to key challenges in achieving high-efficiency single-mode GaN-based ultraviolet (UV) lasers with wavelength ranging from 220 nm up to 300 nm. Particularly, the proposed research will focus on the fundamental physics understanding of the valence band structure of lll-Nitride wide bandgap gain active region, and develop promising solutions on nanostructured quantum wells and fabrication approach of large area GaN-based UV laser arrays. Those lasers would be a promising candidate for various naval applications in sensing and communication.

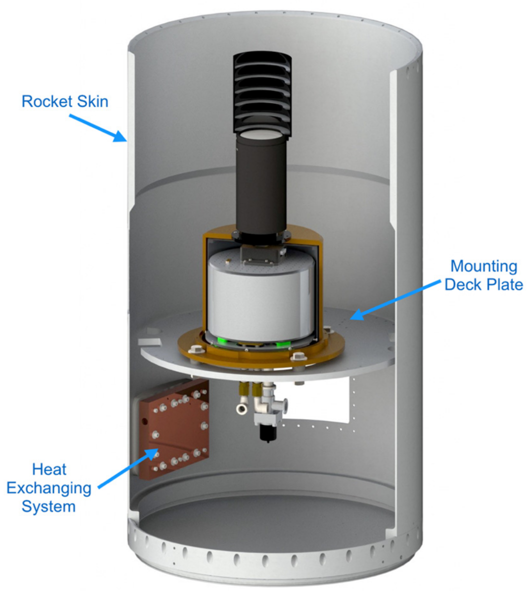
## A Cryogenic Optical Camera for Attitude Control of Low-Temperature Sub-Orbital Payloads

### NASA
### Michael Zemcov

CCDs have been the dominant optical-wavelength detector architecture for high-end optical imaging applications for decades. However, CCDs are inoperable below 120K due to electron freeze-out effects, prohibiting their use in space exploration applications requiring cryogenic temperatures. Mega-pixel CMOS devices are known to work at temperatures as low as 10 K, suggesting that imaging devices based on this technology would operate in cryogenic environments without requiring active heating. In this program, we take the first step to maturing this technology for flight applications in the cryogenic regime by developing and flying an attitude-sensing camera employing a low noise, high quantum efficiency cryogenic CMOS detector. By implementing an alternative imaging technology, we address NASA's major objective to ``transform NASA missions and advance the Nation's capabilities by maturing crosscutting and innovative space technologies.'' This technology enables instruments ranging from actively-cooled star trackers for sounding rockets to low-temperature deep space cameras. As proof of this potential, we use this instrument to enable a scientific study in which we search for diffuse light around galaxies.

In this program, we will take the first step to maturing CMOS technology for flight applications at cryogenic temperature by developing and flying an attitude-sensing camera employing a low noise, high quantum efficiency cryogenic CMOS detector. Images from the 5.5 mega-pixel CMOS sensor operating at 77 K are processed by on-board software, and pointing information is used to determine control inputs to a celestial attitude control system. The instrument (see Figure 19) will first fly on a Black Brant IX (BBIX) technology demonstration flight, followed by a second deployment on a BBIX science mission. This investigation is a hands-on experiential learning experience that has helped to develop the technical and leadership skills of a diverse and multi-disciplinary undergraduate student-led team. The team consists of over a dozen undergraduates, one graduate student mentor, a faculty principal investigator, and two faculty mentors. The undergraduates are currently in the process of executing the project, and have primary responsibility for the mechanical, optical and electrical engineering systems; firmware/algorithm development; flight planning and operations; and documentation and administration. The graduate student and faculty mentors have helped train and advise the team. Over the past year, we designed, built and tested the payload, and took it to the field for integration with the rocket payload. Though we did not successfully launch on our first fielding attempt, the instrument has been returned to RIT and is currently undergoing final testing and software integration. We expect to launch this experiment in the next 12-24 months.





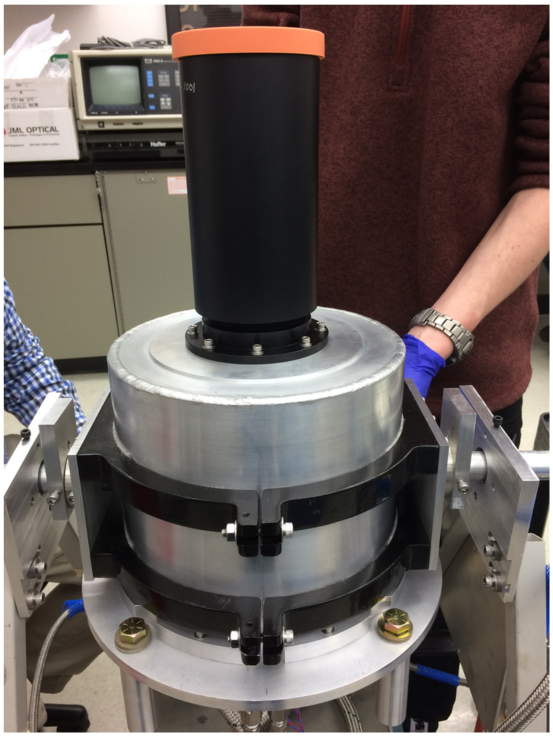



*Figure 19. The image on the left shows a solid model rendering of the instrument that will be launched on a suborbital rocket to validate a cryogenic star tracker. The image on the right is the real-life version of the rendering on the left.*

## Measuring the Pixel Response Function of Kepler CCDs to Improve the Kepler Database

NASA
Zoran Ninkov

The aim of this project is to accurately characterize the intra-pixel response function of Kepler's CCDs and develop a procedure to calibrate data in the Kepler archive and data from the K2 mission. We are measuring the Intra-pixel response function (IPRF) using residual e2v CCD90 detectors, identical to those on the spacecraft, provided to us by the Kepler Project. This IPRF will be used to develop a method to improve the photometry and astrometry of archival NASA Kepler data and data from the K2 mission. The calibration procedure, software, and documentation will be made available to the Kepler community through a new task in the open source community-developed data reduction pipeline, PyKE.

A technique for the direct measurement of intra-pixel sensitivity variations has been developed and used at RIT for a number of years (*c.f.*, Piterman, A, and Ninkov, Z. 2002, Opt. Eng., Vol 41, Issue 6, p. 1192.). Using these methods, an improved high performance measurement apparatus dedicated to the measurement of the IPRF has been built (see Figure 20). This system will be capable of producing spots with full width at half maximum (FWHM) of 3 microns or less, at intervals as small as 0.1±0.02 μm. This allows us to sample Kepler's 27 μm pixels with a wide range of sampling grids – from coarse (10×10) to extremely fine (270×270) (see Figure 21).



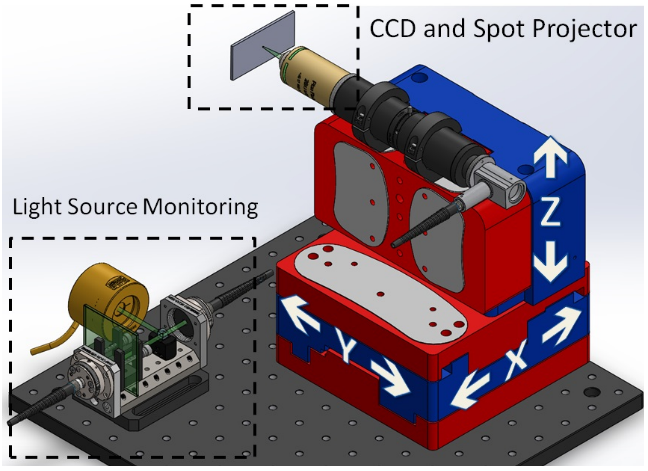



*Figure 20. The experimental apparatus to measure the IPRF of Kepler CCDs – a precise XYZ translation mechanism allows us to illuminate sub-pixel regions with a very fine spacing. By translating the spot projector, we are able to use a variety of cameras and dewars with the CCD. A beam splitter and calibrated photodiode monitor the light source. All elements are connected by optical fibers (not shown).*

The measurement system illuminates a subpixel region on the CCD and measures the response in that location. The spot projector consists of a fiber-illuminated parabolic collimating mirror and a Mitutoyo Plan Apo 20x infinity-corrected microscope objective. This objective is corrected for chromatic aberration over the wavelength range 380 nm–900 nm to provide diffraction-limited performance. Furthermore, the objective has a long working distance (20 mm) which allows us to focus on the pixel surface through the window of a cryogenic dewar. The objective's focal ratio (f/1.25) is well matched to that of Kepler (f/1.47).

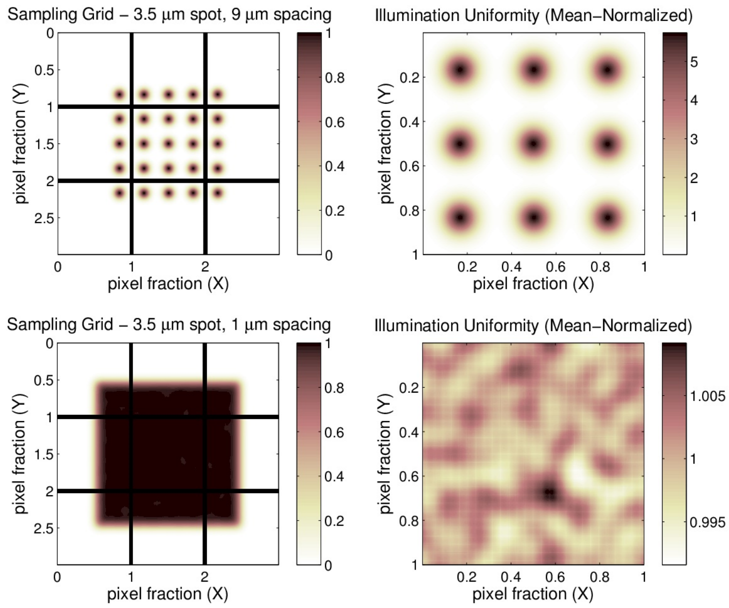



*Figure 21. Using our spot projector, we will be able to illuminate a small region of a single pixel (black lines mark pixel boundaries). We produce a sampling grid by scanning across a pixel and acquiring data at each position. (top row) A simulation of a coarse sampling grid (3×3) and the resulting illumination pattern (very non-uniform). (bottom row) A finer sampling grid (27×27) produces an illumination pattern that is much more uniform (~0.5% non-uniformity).*

Using a broadband source and bandpass filters, we are able to produce arbitrary passbands across Kepler's passband. This ability is critical to characterize the dependence of the IPRF (and consequently the PRF) on the color of a star. Because Kepler has only one passband, it cannot distinguish stars of different colors (Figure 22). However, both the optical PSF and the IPRF depend strongly on the wavelength of light.

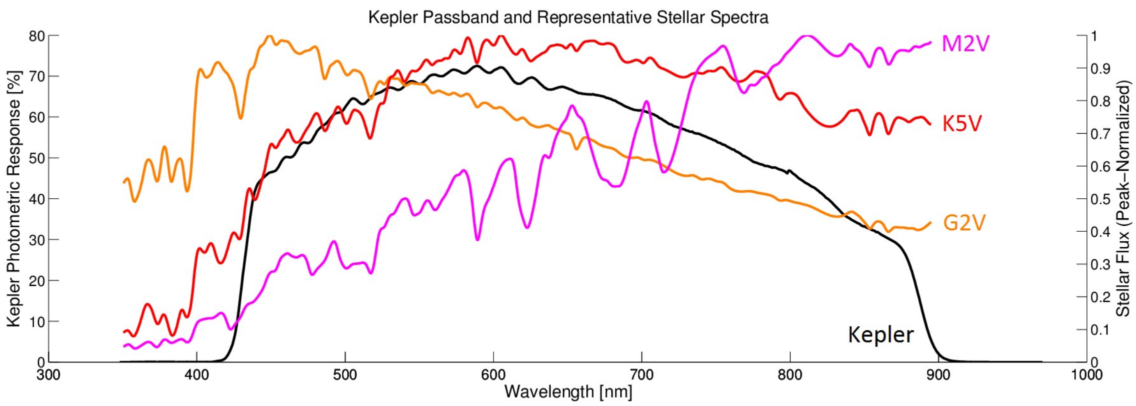



*Figure 22. Kepler observes stars of different colors through one passband. Both the optical PSF of the telescope and the IPRF change with wavelength. Therefore, calibrating the spectral dependence of the IPRF is extremely beneficial. Our measurement apparatus operates across the entire Kepler passband.*

## Ultracompact Graphene Optical Modulators

National Science Foundation
Stefan Preble

The objective of this research is to explore ultracompact graphene optical modulators for future on-chip optical communications. The approach is to systematically explore the unique electro-optic properties of graphene, and to greatly enhance the interaction of graphene with light based on novel waveguides and platforms. In particular, graphene in a waveguide can be tuned with anomalous optical properties with a suitable gate voltage, which will be employed to develop the proposed modulators.

This project systematically explores novel graphene-sandwiched optical waveguides based on the unique properties of graphene. This research will be one of the first experimental attempts to demonstrate optical modulators at nanoscale, and one of the first systematic explorations of graphene for all-optic modulation. The research results may revolutionize nanophotonic technology and on-chip optical interconnects, and will contribute the fundamental theory and techniques for newly developed Graphene Optoelectronics and Graphene and 2D Semiconductor Physics.

Graphene is a topic that is of great interest to the general public. The outreach activity, "From Graphite to Graphene," will help STEM education by introducing K-12 students to the science and fabrication of nanotechnology for a wide range of applications. The students involved in this research participate in nanotechnology development, and the results developed from the research activities will be incorporated into several college courses. Collaboration with external companies may commercialize valuable products for industrial and military applications. Under-represented students from Women in Engineering and North Star Program will be involved in this project.



## Bifacial III-V Nanowire Array on Si Tandem Junctions Solar Cells

National Science Foundation
Parsian Katal Mohseni

Escalating trends in global energy consumption, mandates for increased national energy independence, and mounting alarm regarding anthropogenic climate change all demand improved sustainable energy solutions. While the theoretical power generation potential of solar photovoltaics (PV) in the United States is greater than the combined potential of all other renewable resources, substantial market penetration of PV sand realization of grid-parity have been obstructed by high materials and manufacturing costs, as well as limitations in solar power conversion efficiencies (PCE). A pressing need exists for tandem solar cells utilizing two dissimilar materials (TDM) or more that are capable of PCE values beyond the ~30% Shockley-Queisser limit. In this program we explore a transformative, bifacial solar cell design that employs arrays of TDM III-V compound semiconductor nanowires in tandem with a thinned, intermediate Si sub-cell. The use of epitaxial nanowire arrays overcomes the lattice matching criteria and enables direct III-V on Si monolithic integration. This design eliminates the need for high-cost wafers, growth of graded buffer layers, and anti-reflection coatings, while permitting ideal solar spectrum matching and capture of albedo radiation. The high risk-high payoff and exploratory research fits the NSF EAGER program, as it involves a radically unconventional approach with transformative potential to enable cost-effective manufacturing of high-efficiency TDM solar cells.

## Acquisition of an Inductively Coupled Plasma Reactive-ion Etching System

NSF
Jing Zhang

The inductively coupled plasma reactive-ion etching (ICP-RIE) system provides dry etching capability for various material systems such as compound semiconductors, dielectric materials, and metals with fast etching rate, well-controlled selectivity, and promising uniformity. The instrument is essential to enable fundamental research and education on III-Nitride based light emitting diodes (LEDs) and lasers, seamless integration of robust and low-powered III-V quantum dot (QD) lasers with silicon photonics, III-V tunneling field effect transistor, memory devices for computing, QD and nanowire photovoltaics, III-Nitride photodetectors for inertial confinement fusion research, nanoplasmonic devices, and nan-bio devices for efficient biomolecule transfer. This is the first ICP dry etcher tool at RIT. It is shared by research groups across all disciplines in science and engineering with students trained from Microsystems Engineering PhD program and PhD in Engineering program. The tool is also shared by external research groups in the Rochester region to enhance research and collaborations between RIT and other colleges, national labs, and small businesses.



The ICP-RIE system is a shared user facility, available to new curriculum and lab section development on device fabrications for both undergraduate and graduate students at RIT, whom can be trained for next-generation scientists and engineers. The fabrication capability provided by the instrument benefits curriculum development at RIT for several fundamental courses and lab sections focused on nanofabrication and semiconductor devices. Demonstration experiments on photonic and electronic devices can also be designed to K-12 students and teachers through RIT outreach activities by the use of the dry etcher, which can stimulate K-12 students' interest to pursue science, technology, engineering, and mathematics (STEM) disciplines in the future. Connectivity with such demonstration experiments are promoted to train existing women and underrepresented minority students at RIT.

## AIM Academy Photonic Integrated Circuit Design and Test Education Curricula

AIM Photonics
Stefan Preble

The objective of this multi-year project is to create a curriculum for training a workforce proficient in integrated photonic circuit design. The project will address the needs of prospective PIC designers with course materials on key photonics and integrated circuit design concepts (components and systems, hierarchical design, process design kits, cells/building blocks, circuit simulation, schematic driven layout, design validation and design for manufacturing/test/packaging) presented in contexts relevant to individuals with a comfort zone in either photonics (bottom-up: device to circuit) or electronic chip design (top-down: circuit-to-device). As the AIM Institute's silicon photonics prototyping capabilities come online, these course offerings are intended to provide an on-ramp to a broad set of industry, academic and government lab potential participants in the field. The first courses will be available in early 2018 on MITx. Figure 23 shows a typical application that will be a focal point of education materials created for this activity.

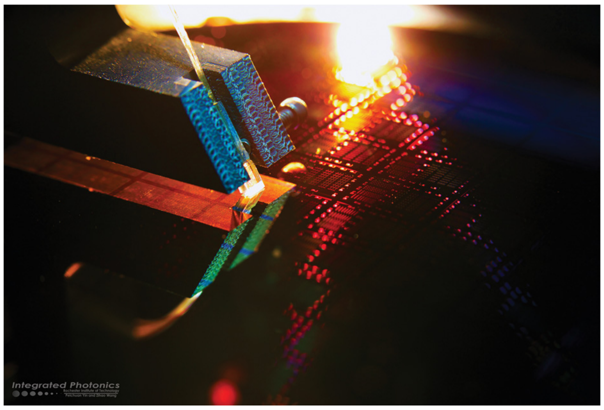



*Figure 23. The picture shows a typical integrated photonic wafer probe.*

## AIM Photonics Test Assembly and Packaging Hub Planning

Air Force/Research foundation of SUNY
Stefan Preble

This projects focus is on the development of advanced test, assembly and packaging (TAP) processes for AIM Photonics TAP hub, a national headquarters for integrated photonic packaging. The project advances PIC manufacturing technology by developing the manufacturing processes necessary to equip a centrally accessible packaging and assembly hub in Rochester, NY. The hub will be equipped for 2.5D electronic/photonic packaging, attach and align tools for fibers and fiber/waveguide arrays, functional testing equipment as well as a full line of metrology tools. The project is well situated for workforce training and education, with six colleges and universities within a short drive, including almost 1000 students majoring in optics, photonics, telecommunications, microelectronics, and manufacturing programs at UR, RIT and Monroe Community College. The project emphasizes the most significant gaps in the manufacturing of PIC-enabled systems by enabling and ensuring access to standardized package designs, integrate the photonic, electronic and physical designs, ensure that metrology tools are available to test the physical integrity of the packages, and provide functional testing for digital, analog, and sensor-based photonic systems. See Figure 24.

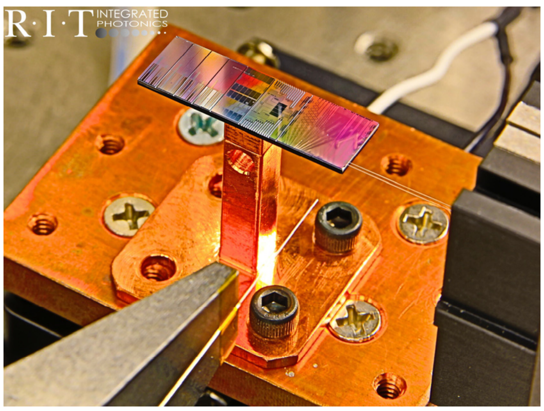



*Figure 24. The picture shows a test setup for an AIM photonic integrated photonic chip.*

## A Data Analysis Pipeline Simulator for a Millimeter-Wavelength Imaging Spectrometer

RIT
Michael Zemcov

This program is a design study for software and data analysis for the Tomographic Ionized-carbon Mapping Experiment (TIME-Pilot) instrument, which is designed to make pioneering measurements of the redshifted 157.7 μm line of singly ionized carbon [CIIJ from the Epoch of Reionization (EoR). The EoR is the period in the Universe's history during which the first stars and galaxies formed, and whose intense ultra-violet (UV) radiation fields ionized the intergalactic medium. The New Worlds, New Horizons 2010 Astrophysics Decadal Report recognized the EoR as one of five scientific discovery areas where "new technologies, observing strategies, theories, and computations open . . . opportunities for transformational comprehension". This investigation has helped break ground for future investment from government and private funding agencies by improving our understanding of the instrument design and expected performance. This OVPR funding has enabled us to build a data acquisition simulation system, and software to talk with the detector readout electronics. A PhD student is currently working on the system, building a real-time data acquisition visualizer and storage code. (Figure 25) We proposed to the 2016 call of the NSF-ATI for full funding for this program, and expect to receive results in mid-2017.

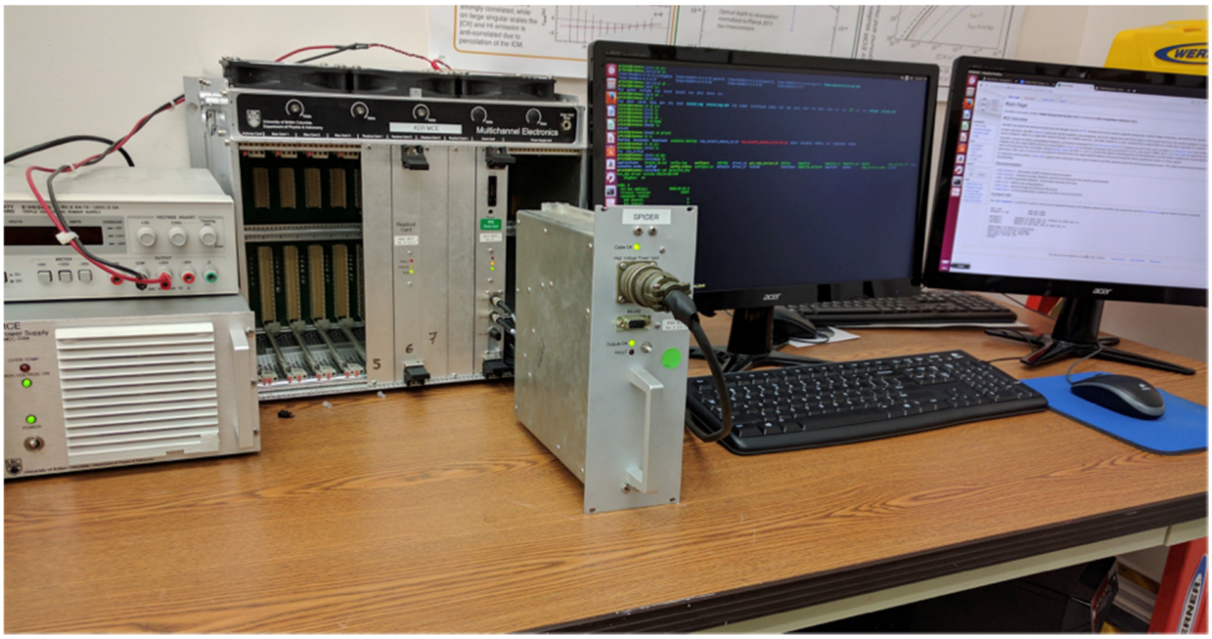



*Figure 25. . The image shows the benchtop setup used to develop a data acquisition and analysis system for the TIME-Pilot instrument*

## Selective Area Epitaxy of III-V Nanocrystals on Graphene and $MoS_2$ for Flexible Optoelectronics Application

RIT
Parsian Katal Mohseni

Atomically-thin, two-dimensional nanomaterials such as single-layer graphene (SLG} and monolayer molybdenum disulfide ($MoS_2$} have emerged as essential building blocks that can enable the development of a widely encompassing class of next-generation nanoelectronic devices. However, these monolayer materials have a critical drawback for applications in optoelectronic, in that they are either inherently incapable (i.e., SLG} of, or are fundamentally inefficient (i.e., $MoS_2$) in, absorbing and emitting light. The purpose of this work is to overcome this limitation through the monolithic integration of highly optically efficient 111-V semiconductor nanostructures with SLG and $MoS_2$ by selective area epitaxial (SAE} crystal growth. This effort aims to combine the characteristic benefits of monolayer materials and 111-V nanocrystals through the synthesis of novel types of hybrid nanostructures. The correlation of extensive structural and optical characterization experiments enables the optimization of SAE growth parameters, and subsequently enable the development of low-cost and high-efficiency flexible light emitting diodes and photodetectors.

# Student Vignettes

## Katherine Seery

Katherine Seery is a graduate student member of the Center for Detectors (CfD) who is working towards completing her PhD in the Astrophysical Sciences and Technology program and an MS in the Imaging Science program. She completed a BA in Physics and Mathematics at Alfred University in 2014. As an undergrad, Katherine completed summer internships on a variety of projects at NASA's Goddard Space Flight Center in 2010 until 2013.

Since coming to RIT in 2014, Katherine has been working with Dr. Zoran Ninkov on developing a Terahertz (THz), or sub-millimeter/millimeter waves, detector using Si-MOSFET CMOS devices. (Figure 26) The devices are designed locally and fabricated using the MOSIS facility. The Terahertz project is a collaboration between RIT, the University of Rochester, and Harris Corporation. Katherine tests the individual MOSFETs that have varied designs to characterize the devices so that they can be implemented into future large focal plane arrays for a variety of applications. She created a custom low noise setup to test the devices. The pixel characterization includes measuring the pixel-to-pixel frequency response, calculating responsivity, noise, *etc*. In addition to pixel characterization, she will be modeling the devices and antennas to attempt to match to the data obtained over the past year. The models will aid in a better understanding of the devices and likely lead to a more tightly integrated THz imaging system.

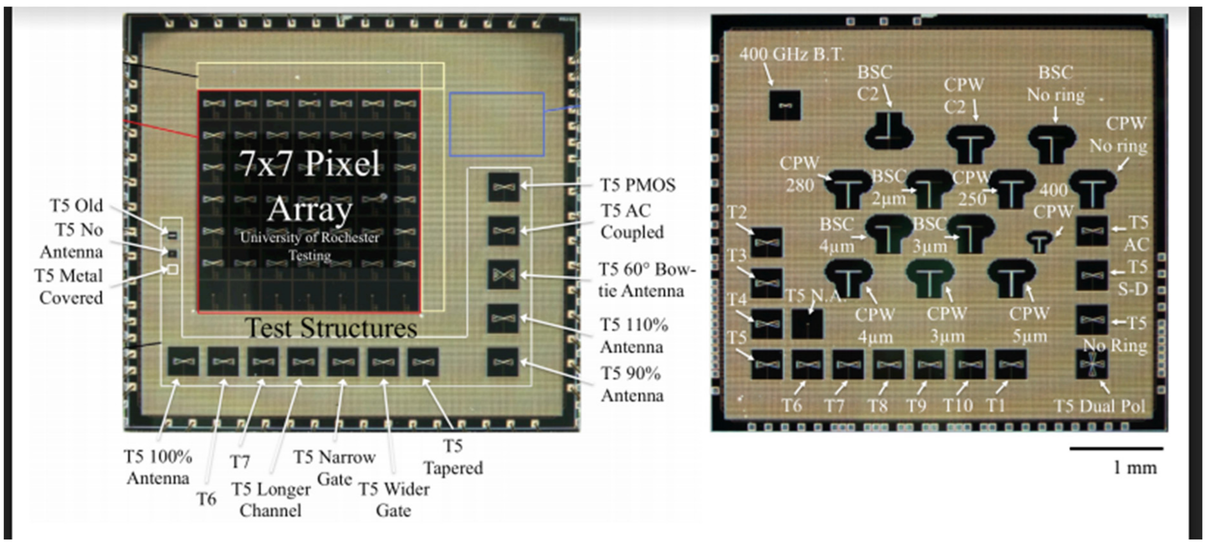
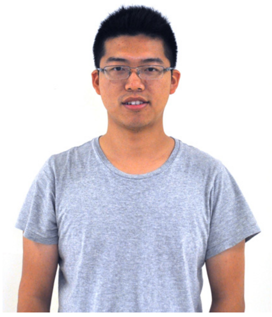



*Figure 26. Devices designed locally for the THz imaging project.*

## Zihao Wang



Zihao Wang is a graduate student member of the Center for Detectors (CfD) who started his PhD in the Microsystem Engineering program in September 2012. He completed his BS degree in opto-electronics in 2012 from Huazhong University of Science and Technology (HUST) in China.

In the senior year of his undergraduate studies, Zihao got chance to exchange to University of Michigan-Dearborn working on his senior design which was developing a method to fabricate anodic aluminum oxide (AAO) membrane template. After completing his BS degree in 2012, Zihao decided to continue to study nanotechnology, with an emphasis on photonic technologies and as a result has been pursuing a PhD with research focused on integrated photonic lasers at RIT.

In the past year, Zihao demonstrated a method to integrate InAs quantum dot (QD) lasers on silicon substrate through palladium (Pd) mediate wafer bonding which is an alternatives to achieve III/V laser on silicon platform. He presented the results of bonded laser as well as QD laser butt-joint coupled to silicon photonic circuits at Integrated Photonics Research (IPR) in Boston, MA, and Photonic West in San Francisco, CA, respectively.



## Mohadesh A. Baboli

Mohadeseh A. Baboli is a graduate student pursuing her PhD degree in the Microsystems Engineering Program. She is a member of the Center for Detectors (CfD) and the NanoPower Research Laboratories (NPRL). Mohad received her BS degree in Electrical Engineering from Babol Institute of Technology in 2010. As a 3$^{rd}$ year undergraduate student, Mohad joined the Integrated Circuits Research Laboratory and conducted research on swarm intelligence-based computational algorithms for discrete optimization problems. In 2011, Mohad continued her studies toward a MS degree in Electrical Engineering at Tehran Azad University. Her focused research areas were on the optical properties of multi-wall carbon nanotube arrays, slow light in infiltrated hole-type photonic crystals, and all-optical logical gates with hopping surface plasmons.

After joining the Microsystems Engineering PhD Program at the Rochester Institute of Technology, Mohad began working on selective area epitaxy of III-V semiconductor nanowires by metal-organic chemical vapor deposition (MOCVD), as part of Prof. Parsian Mohseni's research group (Figure 27). Nanowires are interesting structures because of their relaxed lattice matching capacities and large surface area to volume ratios. In addition, nanowires offer three-dimensional degree of freedom in modifying complex and novel heterostructures. Mohad uses various techniques including scanning transmission electron microscopy (STEM) and photoluminescence (PL) spectroscopy for characterization of semiconductor nanowires, toward device applications in optoelectronics and photovoltaics.


*Figure 27. Mohad is seen here loading a sample in the AIXTRON 3×2 Close Coupled Showerhead metal-organic chemical vapor deposition (MOCVD; RIT NanoPower Research Laboratories) reactor for crystal growth of III-V semiconductor nanowires.*



## Thomas Wilhelm

Thomas Wilhelm is a student in the Microsystems Engineering PhD Program, a member of the Center for Detectors, and the NanoPower Research Laboratories. He completed his BS degree in Physics at Calvin College in 2011. His areas of undergraduate research included the avoided crossing in the normal-mode frequencies of a Wilberforce pendulum, optical heterodyne spectroscopy, and using laser light scattering to measure the effects of monosaccharides on the transition temperatures of phospholipids. Later in 2011, Thomas began his graduate studies at Northern Illinois University where he studied Applied Physics. His areas of research included simulations of field-emission due to nanocathode arrays (in collaboration with the Massachusetts Institute of Technology), and characterization of inorganic silicon oxide molecules deposited onto organic POPC lipid bilayers via chemical vapor deposition (CVD) using scanning tunneling electron microscopy (STEM), energy dispersive x-ray spectroscopy (EDXS), and high angular annular dark field (HAADF) data collected at the Electron Microscopy Center at Argonne National Laboratory (in collaboration with Oklahoma State University). Afterwards, Thomas attended Lehigh University where he completed his ME in Mechanical Engineering in 2014.

Thomas' industry experience includes an extended, one-year internship as a Product Development Engineer before coming to Rochester, NY to accept a position as an Optical Metrology Engineer. Thomas joined RIT's Microsystems Engineering PhD Program in January of 2016.

Thomas is a member of the Mohseni Research Group, working under Dr. Parsian Mohseni on novel, top-down methods for fabrication of III-V and Si nanostructures using metal-assisted chemical etching (MacEtch). MacEtch is an anisotropic, wet-etching technique that relies on catalytic oxidation of a semiconductor substrate underneath a patterned noble metal layer, and preferential dissolution of the selectively oxidized regions (Figure 28). An inherent consequence of this technique is vertical etching of the underlying semiconductor material. Devices consisting of the resulting high aspect-ratio nanostructures have applications in high-efficiency photovoltaics and optoelectronics.

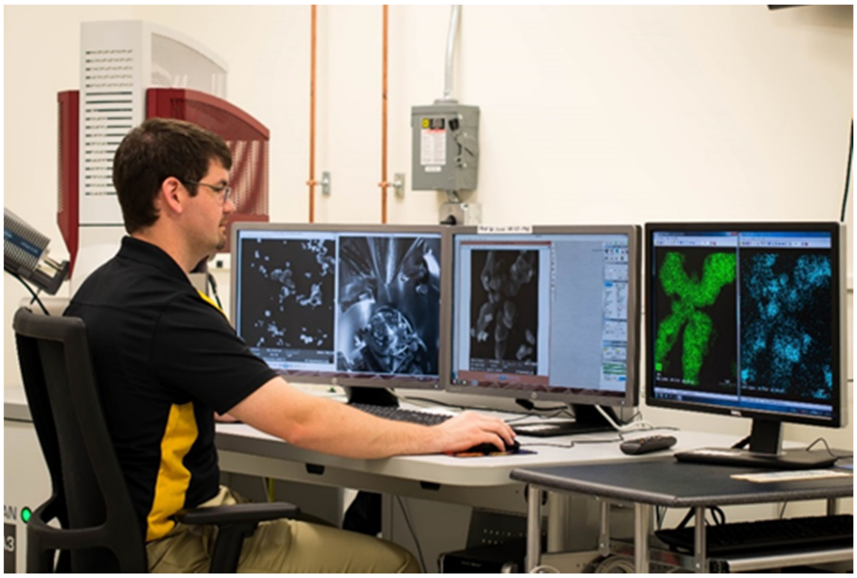


*Figure 28. Tom is seen here using the TESCAN MIRA3 scanning electron microscope (SEM; RIT NanoImaging Lab), where he is analyzing a sample containing Ag nanoparticles on a GaAs substrate for use in MacEtch experiments.*



## Chi Nguyen

Chi H. Nguyen is a graduate student in the Astrophysical Sciences and Technology (AST) Ph.D program and a member of the Center for Detectors. Her advisor is Dr. Michael Zemcov. Before coming to Rochester, she received a BS degree in Astronomy with a Math minor from the University of Arizona (Tucson, AZ).

For her senior thesis Nguyen built a support structure with a robotic actuator for one of the mirrors in the South Pole Telescope Very Long Baseline Interferometry (SPT VLBI) project. The SPT VLBI is part of the Event Horizon Telescope, which uses a network of radio telescopes around the work to directly image the supermassive black hole at the center of the Milky Way. Her instrument was verified and implemented successfully in Antarctica in 2015. In addition to this research, Nguyen worked on various observational projects like studying the properties of exoplanet magnetic field using transit data.

Her Ph.D research focuses on understanding the Extragalactic Background Light (EBL). The EBL probes the history and origin of stellar emission, which allows astronomers to constrain models of star and galaxy formation. She is currently working on the Cosmic Infrared Background ExpeRiment 2 (CIBER-2), which uses a small telescope launched on a Black Brant IX sounding rocket to map the fluctuations in the EBL intensity at near infrared wavelengths. Nguyen leads the mechanical design of many CIBER-2 sub-systems including the payload forward suspension and the radiation shield. In addition, she serves as the graduate mentor of project CSTARS, in which a group of RIT undergraduate students verify the feasibility of flying a scientific CMOS detector on a sounding rocket at cryogenic temperature. The technology of CSTARS is currently being implemented into the CIBER-2 star tracker. After the construction of CIBER-2 is completed, she will develop a data analysis pipeline to extract

EBL information from the flight data. Besides CIBER-2 and CSTARS, Nguyen is also involved with measuring the EBL intensity at visible wavelength using data from the LORRI camera onboard the New Horizons spacecraft. The early result of this project was published in *Nature Communications*.

Nguyen presented her work on CIBER-2 and CSTARS at the AST Jamboree last Fall and at the RIT Graduate Symposium in Spring. She also traveled to the California Institute of Technology (Pasadena, CA) in the Summers of 2016 and 2017 to work directly with the CIBER-2 payload. Recently, she won a NASA Earth and Space Science Fellowship, which will support her future work on the EBL.

## Dmitry Vorobiev

Dmitry finished his PhD last year in Astrophysical Sciences and Technology. He is currently a postdoctoral researcher in the Center for Imaging Science and a member of the Center for Detectors. Dmitry also holds a MS in Imaging Science from RIT. During his time at RIT, Dmitry has worked with Zoran Ninkov on the development of instrumentation for astronomy and remote sensing. His main focus is the development of characterization, calibration, and data analysis techniques for polarization-sensitive imaging detectors based on micropolarizer arrays.

Recently, Dmitry spent two weeks at the Cerro Tololo Inter-American Observatory near La Serena, Chile commissioning the RIT Polarization Imaging Camera on the 0.9 m SMARTS telescope. As part of this run, the instrument was used to observe over 100 calibration standards, star clusters, nebulae, galaxies, and solar system objects. The resulting data was used to show that these sensors are capable of precise imaging polarimetry of a wide range of scenes (see Figure 29). This work paves the way for the adoption of astronomical polarimetric techniques in the fields of remote sensing and biomedical imaging.

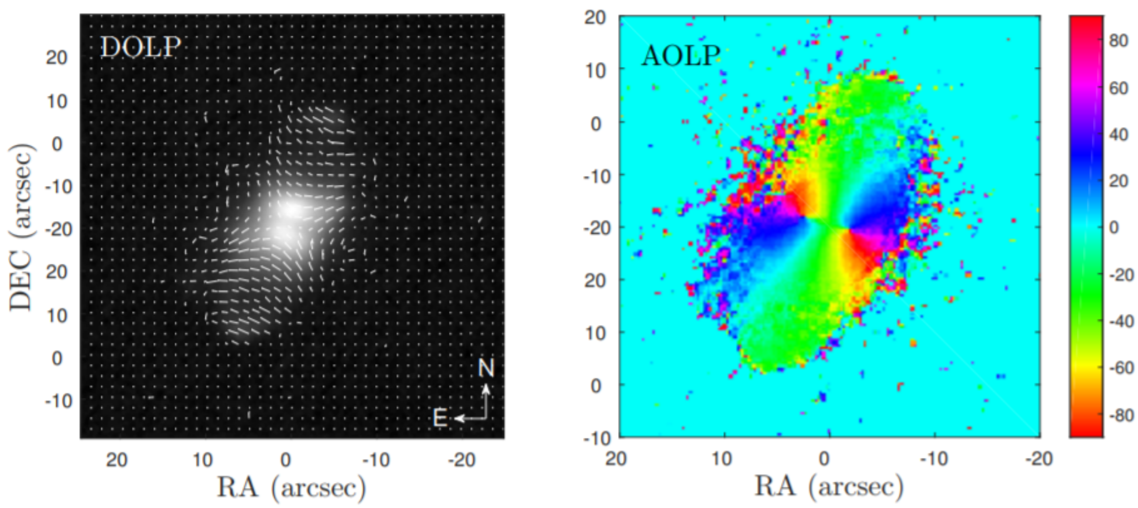



*Figure 29. Left: The image shows the degree and angle of polarization of Frosty Leo, indicated by the length and orientation of the marks. Right: Angle of linear polarization is shown as a colormap.*

## Jeffrey Steidle

Jeffrey Steidle is a PhD candidate in the Microsystems Engineering PhD program. He received his Bachelor of Science in Applied Physics from SUNY Geneseo in 2014. During his undergraduate studies, he worked as a research assistant in the nuclear physics laboratory operating SUNY Geneseo's 1.7 MV Tandem Pelletron Accelerator.

After completing his BS in 2014, he joined the RIT Nanophotonics Group as a graduate research assistant under the advisement of Dr. Stefan Preble and as a member of the Future Photon Initiative. Over the summers of both 2015 and 2016, he has had the opportunity to work with collaborators at the Air Force Research Laboratory (AFRL) in Rome, NY as a visiting scholar under their Visiting Faculty Research Program (VFRP). His research is in photonic devices for UV, visible, and IR wavelengths, specifically, with ring resonator photon sources and their application to quantum integrated photonics. He has experience with all stages of the experiment including design, fabrication, and testing of the photonic circuits.

In the past year he was involved with an experiment in which a silicon ring resonator was used as a photon-pair source (via the third order nonlinear process Spontaneous Four Wave Mixing) and was combined with an on-chip Mach-Zehnder interferometer for the purpose of N00N (N=2) state generation. The state was confirmed through high visibility quantum interference (Figure 1). His most recent work is focused on improvements to the efficiency of these sources by manipulating the couplers on either side of the ring.



## Michael Fanto

Michael Fanto is a graduate student member of the Future Photon Initiative (FPI) conducting research in integrated quantum photonics. He completed his BS degree in Physics from Utica College in 2002. His senior research project was on ultra-fast mode-locked fiber lasers which gave him tremendous experience with nonlinear interactions with materials.

After completing his BS degree, he accepted a position with the United States Air Force/Air Force Research Laboratory (AFRL) in Rome, NY as a research physicist (2002-Present). While at AFRL he has conducted research in a number of areas including fiber laser systems, optical modulators, laser radar, and quantum information science, including quantum computation.

In the summer of 2015 he was awarded an Air Force Development Opportunity package and accepted the admission to RIT to start his PhD in Microsystems Engineering in the integrated photonics group of Dr. Stefan Preble. He has been conducting research on photon pair sources utilizing the third order nonlinearity in silicon and the enhanced efficiency gained from a microring resonator. This research has broadened to include photon generation in the ultraviolet regime, beyond the typically generated infrared photons from silicon. To accomplish this task, one needs a larger bandgap material, and a candidate that can be fabricated into integrated waveguide circuits. The chosen material was aluminum nitride with a bandgap of 6.2 eV, allowing optical transparency well into the ultraviolet. The characterization and generation of photons with aluminum nitride has been the majority of his research conducted over the past year.

## Ben Stewart

Ben Stewart is a graduate student finishing his Masters and Bachelors of Science in Electrical Engineering. He recently joined the CSTARS research group, which is experimenting with the use of CMOS image sensors for rocket guidance in deep space conditions (in collaboration with NASA). Ben's current involvement in the project is the implementation of a new digital sensor, which will increase the effective frame rate of the system by facilitating a much faster operational frequency.

Ben's industry experience includes a co-op in the sensors department at Bosch Security Systems, where he developed and tested ultra-low power intrusion detection systems.

Ben has also been actively involved in the RIT Electric Vehicle Team (EVT), where he has contributed towards an inertial measurement unit, a high-power lithium-ion battery charger, and a lithium-ion battery management system. He is currently the electrical lead for the team.

## Victoria Butler



Victoria Butler is a graduate student pursuing her Ph.D in the Astrophysical Sciences and Technology program. She received her B.S. in Applied Physics with an Astronomy concentration at Rensselaer Polytechnic Institute (Troy, NY) in 2016.

Her current research project is the Tomographic Ionized-carbon Mapping Experiment (TIME), advised by Dr. Zemcov. This millimeter-wave imaging spectrometer will be designed to make measurements of carbon emission from the Epoch of Reionization, probe the Epoch of Peak Star formation through measurements of CO fluctuations, and perform high-speed Kinetic Sunyaev-Zel'dovich (kSZ) surveys of galaxy clusters.

Her contribution will be to utilize the existing Multi-Channel Electronics (MCE) system and modify the Data Acquisition Software (MAS) to communicate with and interpret data produced by the instrument, housed in the closed-cycle cryostat. This will include writing a Python GUI to handle the large quantities of data, and to facilitate communication between the telescope, TIME, MCE, and the user.

# External Funding and Collaborating Partners

Figure 30 shows funding per year since the inception of the Rochester Imaging Detector Laboratory in 2006, and continuing through the period after the Center for Detectors (CfD) was established. A breakdown of current individual grants and contracts is given in the following pages.

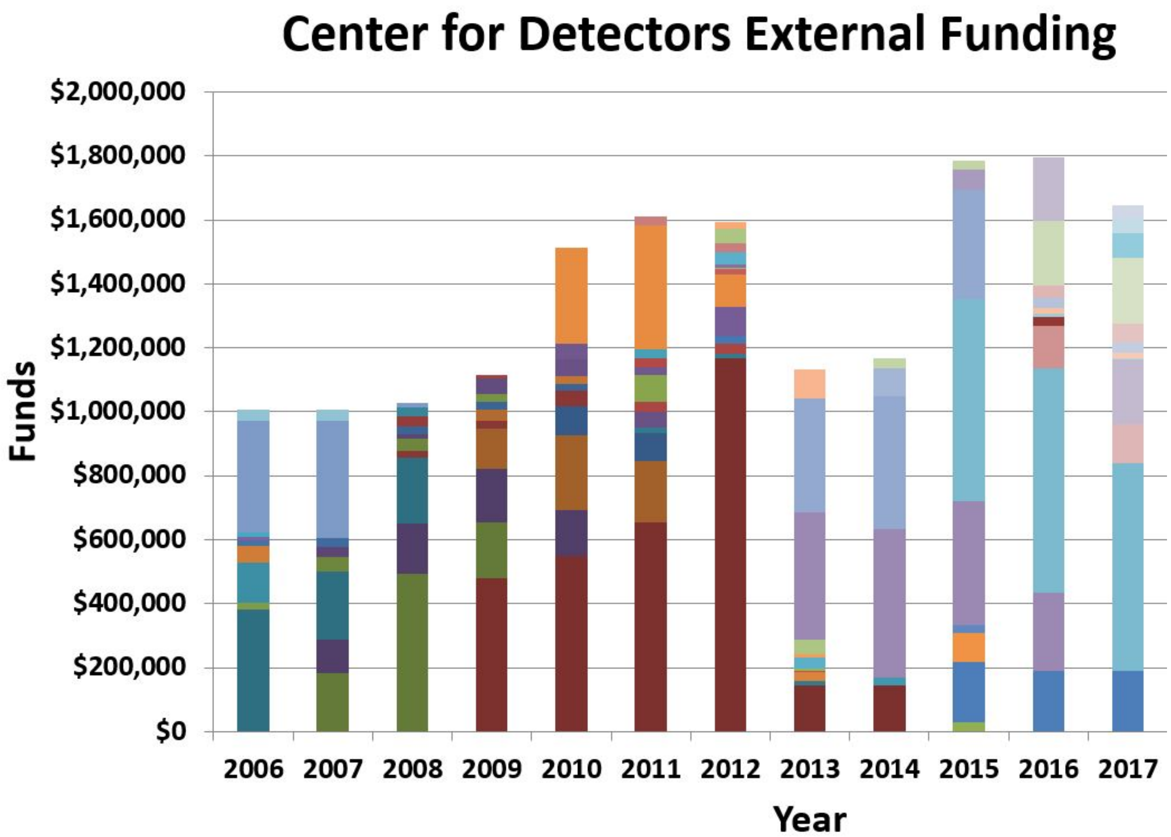



*Figure 30. Since its inception in 2006, the CfD has been awarded over $17M in research funding. The largest contributions are from the Moore Foundation and NASA. The Moore Foundation has awarded $3M to support the development of a zero noise detector, while NASA awarded over $7M in research grants. Each color in the bar chart above represents a unique research program and budget. Most projects have budgets that span multiple years.*

## Grants and Contracts - New

| Title | Funding Source | Dates | Amount |
|---|---|---|---|
| EAGER: TDM solar cells: Bifacial III-V nanowire array on Si tandem junctions solar cells | NSF | 5/1/2017 - 4/30/2019 | $299,808 |
| Quantum Silicon Photonics Measurement System | DOD.Dept of the Air Force, Materiel Command | 9/15/2016-9/14/2017 | $276,475 |
| THz Modeling and Testing | NYSTAR/UR-CEIS | 07/01/2016-06/30/2017 | $30,000 |
| Enhancing the UV/VUV/X-ray sensitivity of CMOS image sensors | NYSTAR/UR-CEIS | 07/01/2016-06/30/2017 | $4,500 |
| Enhancing the UV/VUV/X-ray sensitivity of CMOS image sensors | ThermoFisher | 07/01/2016-06/30/2017 | $18,000 |
| Thz modeling and testing | Harris Corporation | 07/01/2016-06/30/2017 | $60,000 |
| Multi-Color Anisotropy Measurements of Cosmic Near-Infrared Extragalactic Background Light with CIBER2 | NASA/CALTECH | 5/2/2016-5/1/2021 | $308,551 |



## Grants and Contracts - Ongoing

| Title | Funding Source | Dates | Amount |
|---|---|---|---|
| Integrated Quantum Photonics for Photon-Ion Entanglement | USAF | 03/14/2016-03/13/2019 | $600,000 |
| Measuring the Pixel Response Function of Kepler CCDs to Improve the Kepler Database. | NASA | 02/17/2016-02/16/2018 | $246,920 |
| A Photon counting Imaging Detector for NASA Exoplanet Mission | NASA | 02/10/2016-08/31/2018 | $133,000 |
| Phase II: New Infrared Detectors for Astrophysics | NSF | 09/15/2015-08/31/2018 | $1,983,212 |
| The Development of Digital Micromirror Devices for use in Space | NASA | 05/19/2014-05/18/2018 | $565,275 |
| Quantum optical resonators: a building block for quantum computing and sensing systems | NSF | 8/1/2014-7/31/2018 | $349,789 |

## Grants and Contracts - Completed within the Past Year

| Title | Funding Source | Dates | Amount |
|---|---|---|---|
| New Infrared Detectors for Astrophysics | NSF | 06/01/2014-05/31/2017 | $1,490,897 |
| A New VIS/IR Detector for NASA Missions | NASA | 03/01/2013-02/28/2017 | $1,115,106 |
| SPHEREx Design Study for NASA Phase A | NASA/JPL | 12/17/2015-06/01/2016 | $30,000 |
| Enhancing the UV/VUV sensitivity of CMOS Image Sensors | NYSTAR/UR-CEIS | 07/01/2015-06/30/2016 | $9,000 |
| Enhancing the UV/VUV sensitivity of CMOS Image Sensors | Thermo Fisher Scientific | 09/01/2015-06/30/2016 | $18,000 |
| THz Modeling and Testing | ITT Exelis | 07/01/2015-06/30/2016 | $60,000 |

## Collaborating Partners

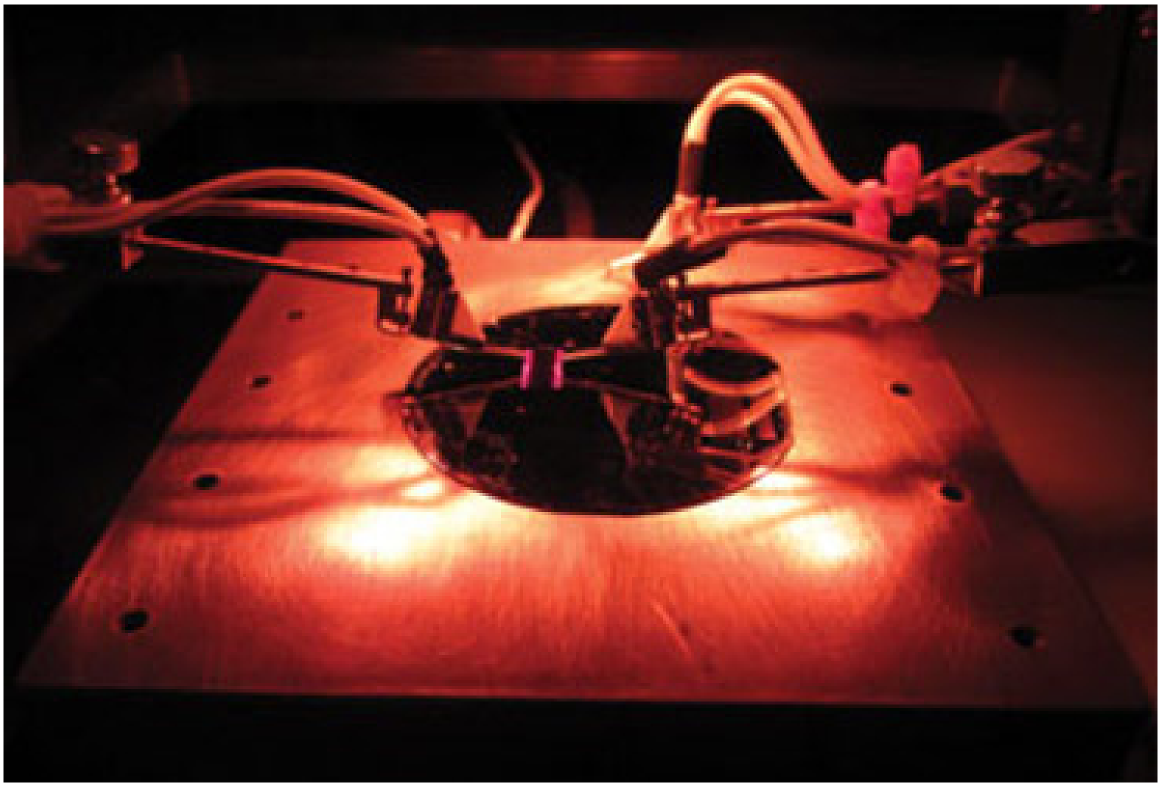
The CfD collaborates extensively with a broad range of organizations, including other academic institutions, government agencies, and industry leaders. Some examples are, NASA, NSF, Thermo Fisher Scientific, Raytheon Vision Systems and the University of Rochester. The vision of the CfD is to be a global leader in realizing and deploying ideal detectors and associated systems, which requires the support of brilliant engineers, passionate philanthropists, and truly inspired industrial partners. Our mission requires a team effort, distributed across several organizations, each with its own world-class expertise and often significant facilities developed over decades of past projects. With appropriate teaming arrangements, this capability can be leveraged in ways that would be impossible if it were necessary to rebuild this infrastructure.

Because of our collaborative approach, and the centrality of student involvement in all of our projects, CfD students benefit from the exposure to a wide range of research and development environments. This is consistent with another major goal of the CfD to train students through deeply immersive work with authentic externally funded research that defines the cutting edge of what is possible. Some students have the opportunity to visit partner organizations for extended periods of time. This training and preparation in the CfD helps students launch their careers after graduation.

## Universities

## National Research Laboratories

## Industry



# Communication

# COMMUNICATION

# In the News

## RIT helps advance space camera being tested on ISS Imaging technology could improve search for distant planets

Published March 6, 2017
By Susan Gawlowicz

Imaging technology advanced by researchers at Rochester Institute of Technology and Florida Institute of Technology is being tested on the International Space Station and could someday be used on future space telescopes.

A new twist on the charge injection device camera, originally developed in 1972 by General Electric Co., fine tunes the array of pixels for improved exposure control in low light conditions. The enhanced technology could give scientists a new method for imaging planets around other stars and improve the search for habitable Earth-like planets.

Zoran Ninkov, professor in RIT's Chester F. Carlson Center for Imaging Science, and Daniel Batcheldor, head of physics and Space Sciences at FIT, designed the charge injection device camera to capture contrasts between light emitted by astronomical objects.

"CID arrays offer considerable promise in many applications due to the focal plane architecture that allows random pixel access and non-destructive readout," said Ninkov, a member of RIT's Center for Detectors and Future Photon Initiative. "In addition to improving presently available devices, the development of next-generation imaging arrays promise considerable flexibility in read-out and on-chip processing for the future."

A SpaceX Falcon 9 rocket, on Feb. 19, carried the charge injection device to the International Space Station in the cargo of supplies and science experiments. Astronauts have installed the camera on a platform outside the space station. They will test the camera for six months.

"We expect to start seeing results by the end of April," said Batcheldor, lead scientist on the project. "A complex test pattern will be sent from a successfully operated camera through the ISS systems and down to the ground. A successful demonstration of CIDs on the International Space Station will put this technology at the NASA Technology Readiness Level 8, which means it's ready to fly as a primary instrument on a future space telescope."

Batcheldor is a former post-doctoral research associate in RIT's School of Physics and Astronomy and a former associate research scientist in RIT's Center for Imaging Science. He and Ninkov have worked together on this experiment for years. They previously have tested charge injection devices from ground-based observatories. Limitations created by the Earth's atmosphere prevent the sensor from capturing images sharp enough to detect planets in other solar systems, Batcheldor noted.

## Undergraduates working with NASA

Published August 10, 2016
By Susan Gawlowicz

Rochester Institute of Technology undergraduates are making a "compass" for rockets using a new kind of detector technology. The instrument will fly on a NASA technology demonstration mission later this year.

The student team is designing, building—and deploying—a telescope and camera that will orient the rocket payload based on the images of stars. RIT's Cryogenic Star Tracking Attitude Regulation System is funded by a $200,000 grant from NASA's Undergraduate Student Instrument Project Flight Research Opportunity program. The NASA program is designed to give undergraduates experience developing and flying experiments relevant to NASA's mission.

RIT professor Michael Zemcov proposed the experiment to test detectors made of metal-oxide semiconductor, or CMOS, a promising new material that can operate at liquid nitrogen temperatures, minus 320 degrees Fahrenheit. These cryogenic temperatures can significantly reduce dark current in the sensor and increase instrument sensitivity. In contrast, the standard technology used in astronomical imaging and in consumer electronics—charge-coupled detectors, or CCDs—is inoperable at cold temperatures.

RIT's prototype represents a step toward a fully cryogenic optical detector that someday could improve the sensitivity of NASA's deep-space cameras, said Zemcov, assistant professor of physics at RIT. The star tracker will fly in a technology demonstration payload on a suborbital sounding rocket that will launch in December from NASA's Wallops Flight Facility on Wallops Island, Va., with experiments from other universities and NASA laboratories. Sounding rockets are cousins of military ordnance, like surface-to-air missiles, which fly to an altitude of approximately 200 miles, and represent an affordable way to conduct science experiments in space.

Following a successful initial flight, a second RIT-built instrument will fly on a NASA rocket experiment to measure the light from faint and distant galaxies. The Cosmic Infrared Background ExpeRiment 2, or CIBER-2, is led by the California Institute of Technology. Zemcov is a member of RIT's Center for Detectors and the Future Photon Initiative and a co-investigator on CIBER-2.



"We needed to build a star tracker for this science payload," Zemcov said. "The problem is that most of the detectors we have don't work at the cold temperatures we require."

The RIT student team brings the specialty of several disciplines to the project. Everyone has a job: Kevin Kruse, a fifth-year BS/MS electrical engineering major from Port Jefferson Station, N.Y., is the electrical engineer and team leader; Chris Pape, a third-year student in the BS/MS program in mechanical engineering technology/mechanical and manufacturing systems integration from Douglassville, Pa., is the mechanical engineer; Benjamin Bonder, a fifth-year BS/MS electrical engineering major from Geneva, N.Y., is the computer engineer; Poppy Immel, a fifth-year BS/MS dual-degree major in computational mathematics and computer science from Castleton, Vt., is the computer scientist; Matthew Delfavero, a third-year physics major from Annapolis, Md., is the physicist; and Hyun Won, a fourth-year international business student born in South Korea and who grew up in Ann Arbor, Mich., is the project manager. Most of the students are using the project as co-op experience.

"The aim is to control this sensor and make it work at cold temperatures," Kruse said. "Then we'll launch it into space to take pictures. A future mission would involve us guiding the rocket using the images we take."

The team's mentors are Zemcov; Dorian Patru, professor of electrical engineering; and Chi Nguyen, a Ph.D. student from Vietnam in the astrophysical sciences and technology graduate program.

"CSTARS will verify a new instrument design, so I'm interested in seeing how well the implemented instrument can meet our expectations," Nguyen said. "As a graduate student, this project is an excellent opportunity for me to gain mentoring experience and experience working with NASA."

## RIT alumnus wins national award for undergraduate physics research Ryan Scott ’16 recognized for developing an experiment for RIT’s quantum mechanics lab

March 7, 2017
By Susan Gawlowicz

A graduate of Rochester Institute of Technology’s College of Science has been recognized by the American Association of Physics Teachers and the Advanced Laboratory Physics Association for his contributions as an undergraduate student researcher to RIT’s School of Physics and Astronomy.

Ryan Scott, who earned his BS in physics from RIT in 2016, has won the AAPT-ALPhA Award for developing a new experiment for the upper-level undergraduate physics lab at RIT. The award also recognizes Scott’s faculty advisers Edwin Hach III, assistant professor of physics, and Stefan Preble, associate professor of microsystems engineering and electrical and microelectronic engineering at RIT. Hach and Preble are both members of the university’s Future Photon Initiative, an RIT signature research area.

Scott will receive his award and $4,000 at the American Association of Physics Teachers meeting in Cincinnati, Ohio, July 22-26, and present his research in an invited talk. Faculty advisers Hach and Preble will also be recognized at the event.

Scott’s experiment can be used as an undergraduate teaching tool to explain concepts that form the basis of quantum computing research. It demonstrates fundamental quantum mechanics by replicating the Hong-Ou Mandel effect to study the behavior of photons, or particles of light. The experiment illustrates superposition and entanglement, fundamental quantum mechanical effects that capture two photons, as a wave and a particle, with one influencing the other at a distance.

RIT gave Scott multiple opportunities to conduct undergraduate research and to be part of the Center for Detectors during his senior year, he said.

“I worked in a condensed matter lab on theoretical modeling for simple photonics devices and wrote software to mathematically model a laser deforming silicon crystals,” Scott said. “I especially appreciated so many professors being excited to work with students.”

Scott develops and implements software at Epic Systems Corp. in Madison, Wis. He is originally from Shrewsbury, Mass.

## The Next Revolution: Integrated Photonics

**By Stefan Preble, Microsystems Engineering, Kate Gleason College of Engineering, RIT**

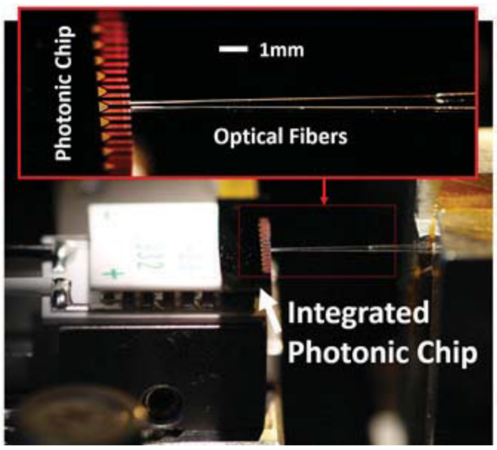
Integrated Photonics is the intersection of microelectronics and photonics. Microelectronics has been the driver of technology and the world’s economy for several decades. Its success is a direct result of the integrated circuit where billions of electrical components (transistors, wires, resistors, capacitors, etc.) are seamlessly integrated together on silicon wafers using manufacturing processes that have followed the scaling trends of Moore’s law. Photonic technologies are now at a point similar to where microelectronics was at in the early 1970’s - where just a relatively small number of components were tediously integrated together. However, by leveraging the manufacturing equipment and techniques that made microelectronics a success, it is now beginning to be possible to realize the same economies of scale to make integrated photonic circuits. Furthermore, since similar manufacturing technologies are being used, photonics and electronics can be directly integrated together to make both the electronic and photonic elements of the circuits function better - not only reducing size, weight and power but enabling entirely new applications, many of which have not been envisioned (see Figure 31).

In order to understand integrated photonics a general overview of photonics is needed. Photonics is the study of the generation, manipulation and detection of light. Light is made up of photons, similar to how electric current is made up of individual electrons. However, photons have the distinct advantage that they travel at the speed of light and don't consume any power during their propagation. For example, photons routinely travel across the entire universe (albeit after approximately thirteen-billion years) with just the energy required to initially produce them. Photons are also very efficient information carriers. They are an electromagnetic wave (just like a radio wave) that oscillates at very high frequencies, on the order of 200 THz (200 × 1012 Hz), and as a result can easily encode terabytes/second of information in their amplitude, phase or polarization.

There have been many platforms for photonics over the decades, such as fiber optics where discrete components (lasers, the actual fiber optic cable, which transmits light and detectors) are separately manufactured and put together. In the 1990's the first steps towards integrated photonics were made with the development of planar lightwave circuits (PLCs), based on glasses that are patterned using photolithography or directly written by modifying the material using lasers. PLCs are still commonly used today and allow light to be guided and manipulated to interfere with itself, enabling switches and filters. However, the PLC platform illustrates the challenges of realizing truly integrated photonics. Specifically, the large size of the glass waveguides limits the ability to scale the circuit's complexity (because of the limitations of total internal reflection) and more importantly, it is challenging to integrate the lasers and detectors on the same PLC chip because of the dissimilar material and manufacturing platforms.



To continue reading about the future of integrated photonics in our lives, please go to: [http://ridl.cfd.rit.edu/products/press/rochesterengineeringsociety/2015septembere-issuestefanpreble.pdf](http://ridl.cfd.rit.edu/products/press/rochesterengineeringsociety/2015septembere-issuestefanpreble.pdf)



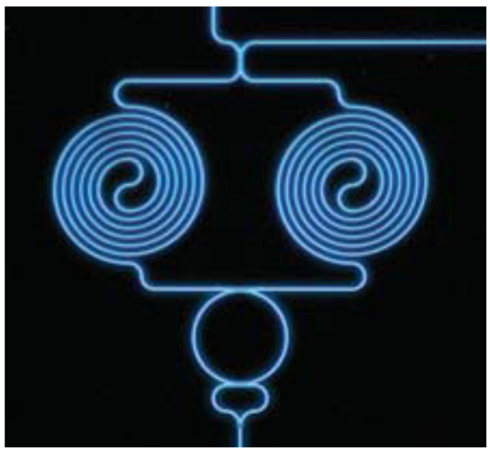



*Figure 31: (left) The images above show an integrated photonic chip connected to two optical fibers and (right) silicon photonics for quantum computing that are being developed for future application.*

# Publications


- Zemcov, Michael, Immel, Poppy, Nguyen, Chi, Cooray, Asantha, Lisse, Carey M., and Poppe, Andrew R. 2017, Measurement of the cosmic optical background using the long range reconnaissance imager on New Horizons, Nature Communications, Online Volume 8, SP 15003
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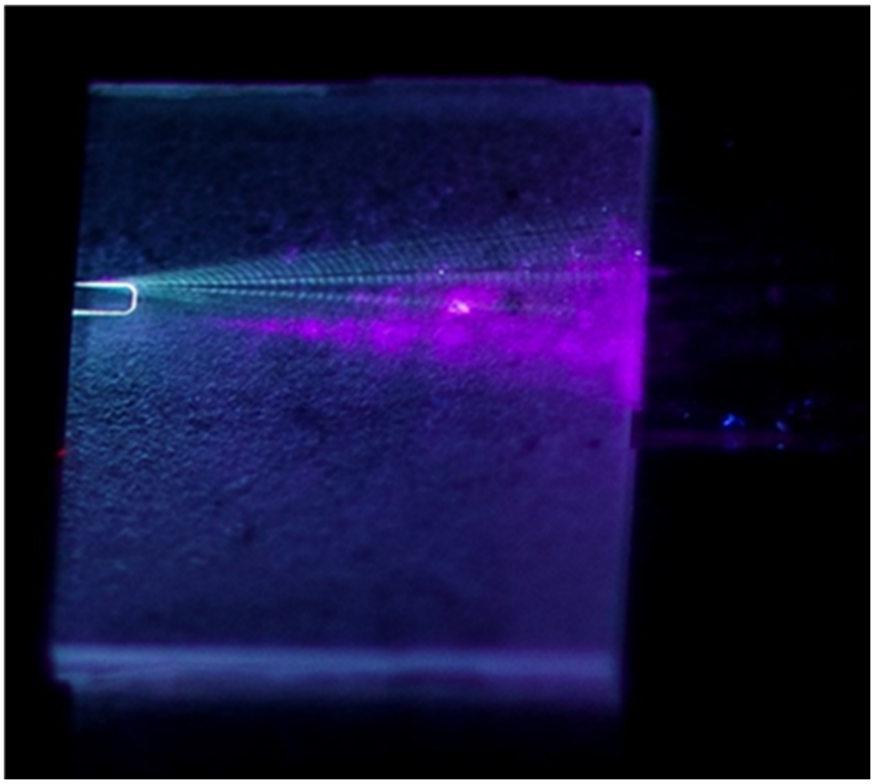
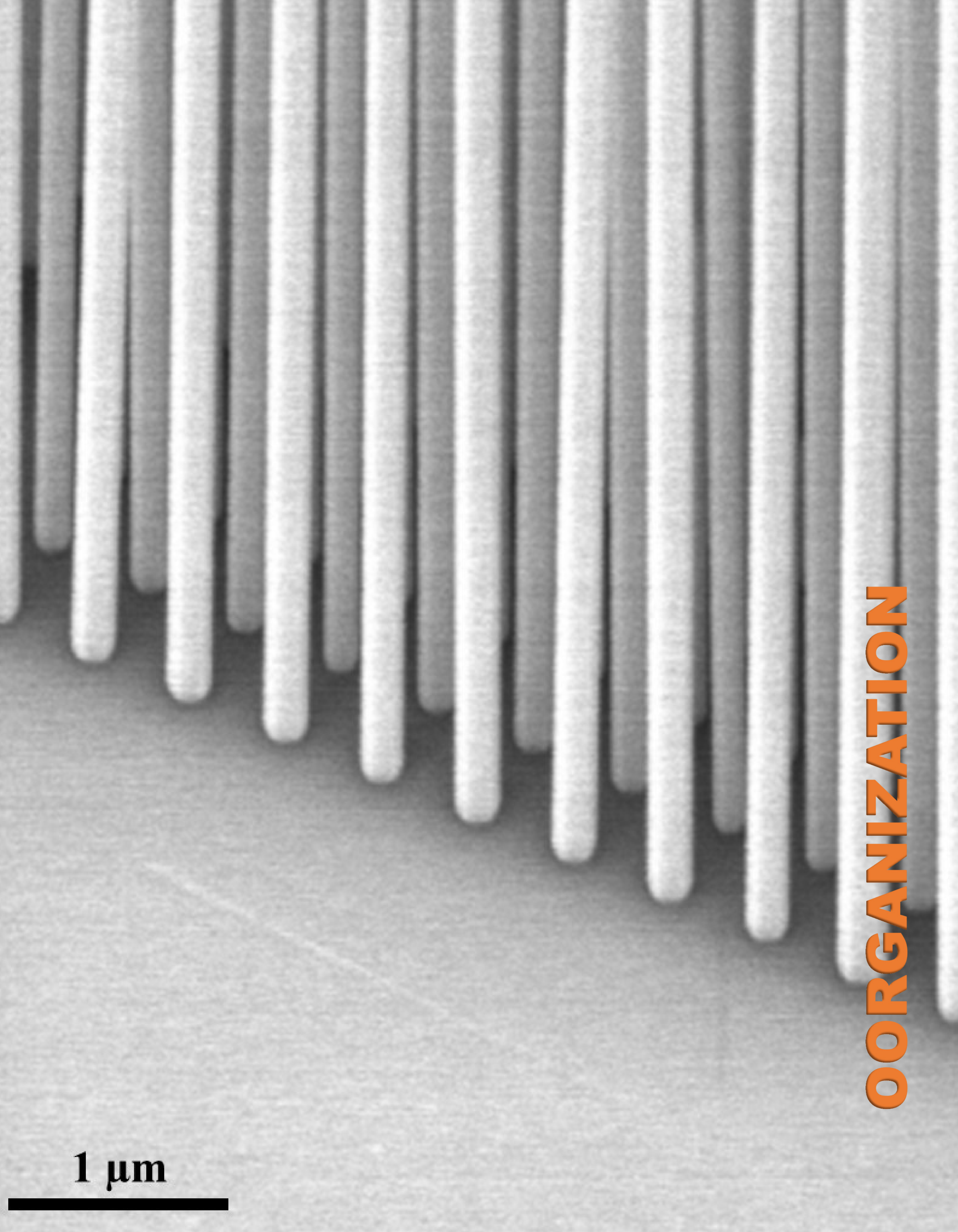


# Organization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# Personnel

**Don Figer**

Director, Professor

Degree(s): PhD in Astronomy, 1995, UCLA; MS in Astronomy, 1992, U. Chicago; BA in Physics, Math, Astronomy, 1989, Northwestern U.

Dr. Figer is the Director of both the Center for Detectors and the Future Photon Initiative, as well as a Professor in the College of Science. Dr. Figer's research within the Center for Detectors is dedicated to the development of advanced imaging detectors for cross-disciplinary applications.

Dr. Figer led many research projects within the Center for Detectors over the past year. Some of the major projects are New Infrared Detectors for Astrophysics, New Visible/IR Detectors for NASA Missions and A Photon Counting Imaging Detector for NASA Exoplanet Mission. Research interests of Dr. Figer are developing integrated sensor systems on a wafer, and to determine massive star content in the Local Group of galaxies.

Dr. Figer has received numerous awards for his work, including the NYSTAR Faculty Development Award, The NASA Space Act Award, and the AURA STScI Technology, and Innovation Award.

**Zoran Ninkov**

Professor

Degree(s): PhD, Astronomy, University of British Columbia, 1986; MSC., Physical Chemistry, Monash University, 1980; BSC. (1st class honors), Physics, University of Western Australia, 1977.

Dr. Ninkov's scientific background includes Solid State Image Sensors, Robotic Astronomy, Planetary Searches, Astronomical Imaging, and Digital Radiography.

Dr. Ninkov's current research is focused on the development of novel two dimensional detector arrays for use in spaceborne and ground based astronomical imaging and spectroscopy, in particular the development of the Active Pixel or Pre-Amp Per Pixel Sensor, the successor to the acclaimed CCD. Dr. Ninkov's effort has involved design and fabrication of these devices in the RIT Micro-Electronics/Electrical Engineering Department. Other research concentrations are the development of image processing techniques for optimal analysis of such two dimensional (InSb, NICMOS, CCD, CID and APS arrays) astronomical image data and the study of fundamental limitations of such devices.

Dr. Ninkov also serves as the Associate Director at the C. E. K. Mees Observatory at the University of Rochester, a position he has held since 1995.

**Stefan Preble**

Associate Professor

Degree(s): PhD, Electrical & Computer Engineering, 2007, Cornell University; BS in Electrical Engineering, 2002, Rochester Institute of Technology

Dr. Preble is Associate Professor in the College of Engineering and the lead of the Lobozzo Photonics and Optical Characterization Lab. Dr. Preble's research concentrations are Quantum Computing, Communication and Sensing, Photonics Packaging, and integrated photonics education. This research is focused on novel silicon photonic devices with the goal of realizing high performance computing, communication, and sensing systems that leverage the high speed, bandwidth, and sensitivity of light.

Dr. Preble has received numerous awards recognizing his work, including a DARPA (Defense Advanced Research Projects Agency) Young Faculty Award and an AFOSR (Air Force Office of Scientific Research) Young Investigator Award. He has numerous publications in high impact journals, such as Nature Photonics, Optics Express, Applied Physics Letters, and Physical Review Letters. He is a member of the Optical Society of America.

**Jing Zhang**

Assistant Professor

Degree(s): PhD in Electrical and Computer Engineering, 2013, Lehigh University; BS in Electronic Science and Technology, 2009, Huazhong University of Science and Technology.

Dr. Zhang is an Assistant Professor in the College of Engineering. Dr. Zhang's research areas are related to III-Nitride semiconductors for photonics and energy applications. Her research interests include the pursuit of novel materials for large thermoelectric figure of merit, semiconductor Ultraviolet Light Emitting Diodes (LEDs) and lasers, as well as III-Nitride solid state lighting devices.

Dr. Zhang has worked on compound semiconductors, and gallium nitride as an emerging material being applied. Gallium nitride-based semiconductors are being integrated into optoelectronics, such as LEDs, to power electronics for smart grid applications and power management for electric vehicles. These semiconductors find solar applications as well. She has expertise in the area of ultraviolet and visible LEDs, and in developing semiconductors for optoelectronic and electronic devices.

Dr. Zhang has published more than 22 refereed journal papers and 30 conference publications, including invited talks.

**Michael Zemcov**

Assistant Professor

Degree(s): PhD in Physics, Cardiff University, 2006, Cardiff, United Kingdom; BS in Physics, 2003, University of British Columbia, Canada

Dr. Zemcov is an Assistant Professor in the College of Science and an experimental astrophysicist at the Future Photon Initiative and Center for Detectors. His scientific background and interests are centered on cosmological observations of the large-scale structure of the universe, and studies of fundamental physics. His expertise includes studies of the diffuse radiation in the cosmos, particularly the cosmic microwave and infra-red background radiation, and the development of enabling technologies for ground-based, sub-orbital, orbital, and deep-space platforms.

Dr. Zemcov works on a number of projects, which aim to elucidate the nature of the cosmos on the largest scales and most distant times. He is also engaged in efforts to deploy CMOS devices for astronomy, develop technologies for astrophysics from the outer solar system, various large mission concept studies, and other niche cosmological and physics experiments requiring bespoke instrumentation.

**Parsian K. Mohseni**

Assistant Professor

Degree(s): PhD in Engineering Physics, 2011, McMaster University, Canada; B.Eng. in Engineering Physics, 2005, McMaster University, Canada

Dr. Mohseni is an Assistant Professor in the College of Engineering, and Head of the Epitaxially-Integrated Nanoscale Systems Laboratory. Dr. Mohseni's research interests are cross-disciplinary, spanning the fields of solid state physics, optoelectronics, materials characterization, nano-engineering, and physical chemistry. He is interested in novel, bottom-up and top-down methods for fabrication of III-V and Si nanostructures for applications including solar cells and photodetectors.

Dr. Mohseni's research involves epitaxy of III-V semiconductors on 2-D nanosheets, and focuses on the growth of various nanostructures, including nanowires and nanofins, by metal-organic chemical vapor deposition (MOCVD) through a synthesis process known as selective area epitaxy (SAE). Additional research paths include metal-assisted chemical etching for room temperature and benchtop fabrication of flexible III-V nanostructure-based optoelectronic and photovoltaic devices.

**Joong Lee**

Engineer

Degree(s): PhD in Physics, 2007, UCLA; BS in Physics, 1998, UC Berkeley

**Brandon Hanold**

Engineer

Degree(s): BS in Astrophysics, 2006, Michigan State University

**Robyn Rosechandler**

Senior Staff Assistant, Future Photon Initiative

Degree(s): BS in Mass Communications, Dec 2013, Black Hills State University

**Victoria Butler**

PhD Student, Astrophysical Sciences

Degree(s): BS in Applied Physics, May 2016, Rensselaer Polytechnic Institute

**Kenton Weigold**

Software Architect

Degree(s): BS in Computer Engineering, 2007, Rochester Institute of Technology

**Bryce Tennant**

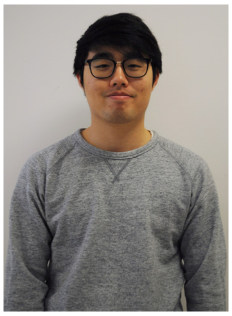
PhD Researcher, Microsystems Engineering

Degree(s): MSEE in Electrical Engineering focus in Signal Processing, 2004, Rochester Institute of Technology; BSEE in Electrical Engineering, 1997, Rochester Institute of Technology

**Thomas Benedett**

Senior Systems Engineer

Degree(s): BS in Electrical Engineering, 1984, Rochester Institute of Technology



**Hyun Won**

Executive Assistant

Degree(s): BS in International Business, May 2017, Rochester Institute of Technology

**Nina Wilson**

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Degree(s): BS in International and Global Studies & Anthropology, May 2019, Rochester Institute of Technology

**Dwayne Thomson**

Executive Assistant

Degree(s): BS in Management Information Systems, May 2019, Rochester Institute of Technology

**Philip Linden**

Lab Assistant

Degree(s): BS/ME in Mechanical Engineering, May 2017, Rochester Institute of Technology



**Anton Travinsky**

Ph.D Researcher, Imaging Science

Degree(s): BS in Mechanical Engineering, Technion, Israel, MS Electrical Engineering, WRTH Aachen University, Germany

**Jack Horowit**
MS Researcher, Imaging Science
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**Bryan Fodness**
MS Researcher, Imaging Science
Degree(s): BS in Physics, May 1999, Bloomsburg University of Pennsylvania

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Degree(s): BS/MS in Computational Mathematics and Computer Science, May 2017, Rochester Institute of Technology



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Degree(s): BS/MS in Electrical Engineering, May 2017, Rochester Institute of Technology

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PhD Researcher, Astrophysical Sciences and Technology

Degree(s): BA in Physics and mathematics, May 2014, Alfred University

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Degree(s): BS in Mechanical Engineering Technology/Physics, May 2022, Rochester Institute of Technology

**Kevan Donlon**

PhD Researcher, Imaging Science

Degree(s): BS in Physics, 2012, Rensselaer Polytechnic Institute

**Nicholas Bitten**

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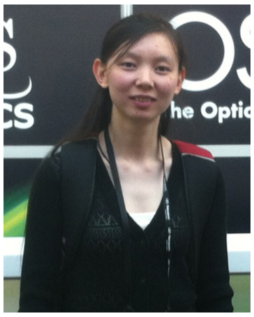
Degree(s): BS in Physics, May 2017, Rochester Institute of Technology



**Yukee Ooi**

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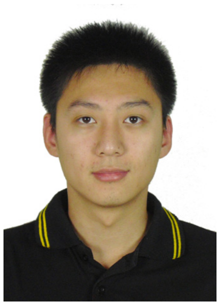
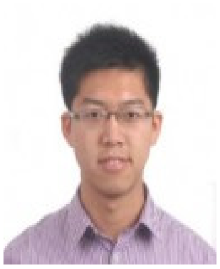
Degree(s): BEng in Computer Engineering, May 2011, Hong Kong University of Science and Technology



**Cheng Liu**

PhD Researcher, Microsystems Engineering

Degree(s): BS in Physics, June 2013, Wuhan University, China



**Zihao Wang**

PhD Researcher

Degree(s): BS in Opto-electronics, Huazhong University of Science and Technology

**Chi Nguyen**

PhD Researcher, Astrophysical Sciences and Technology

Degree(s): BS in Astronomy, 2015, University of Arizona

**Jeffrey Steidle**
PhD Researcher, Microsystems Engineering
Degree(s): BS in Physics, 2014, State University of New York at Geneseo

**Michael Fanto**
PhD Researcher, Microsystems Engineering
Degree(s): BS in Physics, 2002, Utica College of Syracuse University

**Dmitry Vorobiev**
PhD Researcher, Astrophysical Sciences and Technology
Degree(s): PhD in; BS in Astrophysics, University of New Mexico.



**Paul Thomas**
Postdoctoral Fellow
Degree(s): PhD in Microsystems Engineering, May 2015, Rochester Institute of Technology

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Lab Assistant

Degree(s): BS in Imaging Science, May 2019, Rochester Institute of Technology

**Suvam Bag**

Software Developer

Degree(s): MS in Computer Engineering, December 2016, Rochester Institute of Technology

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PhD Researcher, Microsystems Engineering

**Mohadeseh Baboli**

PhD Researcher, Microsystems Engineering

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Degree(s): BS/MS in Mechanical Engineering Technology, May 2019, Rochester Institute of Technology

**Benjamin Bondor**

Lab Assistant

Degree(s): BS in Electrical Engineering, May 2017, Rochester Institute of Technology

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High School Intern

Degree(s): High School Graduate, June 2018, Fairport High School


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Student Programmer

Degree(s): BS in Imaging Science, May 2017, Rochester Institute of Technology

**Nate Rummage**

Undergraduate Student Researcher

Degree(s): BS in Electrical Engineering, May 2018, Rochester Institute of Technology

**Ben Stewart**

Undergraduate Student Researcher

Degree(s): BS in Electrical Engineering, May 2018, Rochester Institute of Technology

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Degree(s): BS in Electrical Engineering, May 2021, Rochester Institute of Technology

**James Godzwan**

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Degree(s): BS in Electrical Engineering, May 2018, Rochester Institute of Technology

**Nate Tiberio**

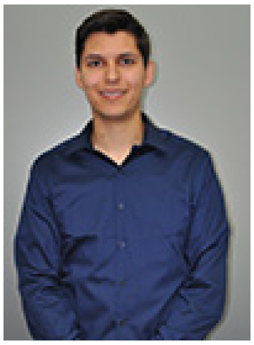
Undergraduate Student Researcher

Degree(s): BS in Electrical Engineering, May 2018, Rochester Institute of Technology

**Ambar DeSantiago**

Undergraduate Student Researcher

Degree(s): BS in Imaging Science and Applied Math, May 2018, Rochester Institute of Technology



**Justin Beigel**

Student Programmer Co-op

Degree(s): BS/MS in Electrical Engineering, May 2020, Rochester Institute of Technology

# Charter

## About the Center for Detectors

The CfD designs, develops, and implements new advanced sensor technologies through collaboration with academic researchers, industry engineers, government scientists, and students. The CfD enables scientific discovery, national security, better living, and commercial innovation through the design and development of advanced photon detectors and associated technology in a broad array of applications such as astrophysics, biomedical imaging, Earth system science, and inter-planetary travel.

## Vision and Mission

Our Vision is to be a global leader in realizing and deploying ideal detectors and associated systems. Our Mission is to enable scientific discovery, national security, better living, and commercial innovation through the design and development of advanced photon detectors and associated technology by leveraging collaborations with students, scientists, engineers, and business partners, at academic, industrial, and national research institutions.

## Goals

- Develop and implement detector technologies that enable breakthroughs in science, defense, and better living.
- Train the next generation of U.S. scientists and engineers in team-based, interdisciplinary, world-class research.
- Create opportunities for faculty, students, and international leaders to advance the field of detectors and its relevant application areas.
- Grow externally-supported research.
- Increase economic activity for local, regional, and national companies.

## Focus Areas

The Center seeks to apply its technologies to many different scientific areas including Astrophysics, Biomedical Imaging, Defense, Earth Systems Science, Energy, Homeland Security, and Quantum Information. These focus areas are mainly what brings together the great variety of individuals from diverse areas of expertise.

Astrophysics – Low noise detectors will enable the discovery of Earth-like planets around nearby stars, life on other planets, the nature of dark energy and dark matter, and the origins of stars and galaxies.

Biomedical Imaging – Implementation of biophotonic sensing systems will enable safe detection and monitoring of breast cancer and cognitive functioning with unprecedented sensitivity.

Defense – Space-based cameras will be equipped with the most sensitive detectors that provide rapid delivery of the most sensitive information.

Earth Systems Science – The Center's detectors will be exploited to address fundamental Earth system science questions.

Homeland Security – Advanced-imaging detectors will be able to reveal potential airborne biochemical hazards through high-resolution three-dimensional ranging, spectral discrimination, and motion pattern recognition.

Quantum Information – High-speed single photon receivers will be deployed to support future technologies in photonics, communication, quantum computing, and quantum cryptography.

# Capabilities, Equipment, and Facilities

The Center for Detectors (CfD) is located in Engineering Hall (Building 17) at the Rochester Institute of Technology. The CfD headquarters consists of 5,000 square feet of office and research laboratory space. Included in the headquarters lab space are the Rochester Imaging Detector Laboratory (see Figure 32), the laboratory for Experimental Cosmology, the Lobozzo Photonics and Optical Characterization laboratory, and the Semiconductor Device Optical Property Measurement lab.

*Figure 32. Above is the main CfD lab, the Rochester Imaging Detector Laboratory.*

Facilities within in CfD include a permanent clean room, ESD stations, vacuum pumping systems, optical benches, flow tables, light sources, UV-IR monochromators, thermal control systems, cryogenic motion control systems, power supplies, general lab electronics, and data reduction computers and more. The equipment is capable of analyzing both analog and digital signals. Separate rooms in the CfD are devoted to electrical rework and laser experiments. In addition to these dedicated facilities, the CfD has access to facilities within the Semiconductor and Microsystems Fabrication Laboratory (SMFL) and other areas across the RIT campus.

The RIDL detector testing systems use four cylindrical vacuum cryogenic dewars. Each individual system uses a cryo-cooler that has two cooling stages: one at ~60 K (10 W) and another at ~10 K (7 W). The cold temperatures yield lower detector dark current and read noise. The systems use Lakeshore temperature controllers to sense temperatures at 10 locations within the dewars and control a heater in the detector thermal path. This thermal control system stabilizes the detector thermal block to 400 μK RMS over timescales greater than 24 hours. The detector readout systems include an Astronomical Research Camera controller having 32 digitizing channels with 1 MHz readout speed and 16-bit readout capability, two Teledyne SIDECAR ASICs having 36 channels and readout speeds up to 5 MHz at 12-bits and 500 kHz at 16-bits, custom FPGA systems based on Altera and Xilinx parts, and a JMClarke Engineering controller with 16 readout channels and 16-bit readout designed specifically for Raytheon Vision System detectors. The electronics packages are shown in Figure 33.

*Figure 33. The three electronics packages used to test detectors are shown here. Electronics from left to right: Astronomical Research Camera Controller; JMClarke Engineering, Teledyne SIDECAR ASIC.*

The controllers drive signals through cable harnesses that interface with Detector Customization Circuits (DCCs), which are designed in-house and consist of multi-layer cryogenic flex boards. The DCCs terminate in a single connecter, which then mates to the detector connector. Three-axis motorized stages provide automated lateral and piston target adjustment. Two of the dewars have a side-looking port that is useful for exposing detectors to high energy radiation beams. The lab also has two large integrating spheres that provide uniform and calibrated illumination from the ultraviolet through the infrared, and they can be mounted to the dewars. The dewars are stationed on large optical tables that have vibration-isolation legs (Figure 34).

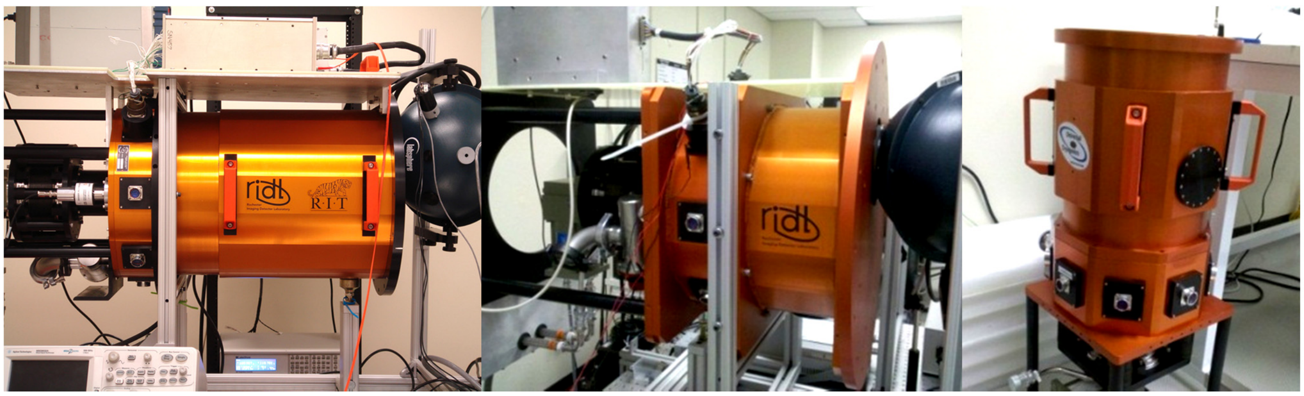



*Figure 34. Detectors are evaluated in four custom dewar test systems. The fourth dewar is a duplicate of the one pictured on the left.*

The lab equipment also includes a Pico Quant laser for LIDAR system characterization and other testing that requires pulsed illumination. In addition, the lab has monochromators with light sources that are able to produce light ranging from the UV into the IR, with an approximate wavelength range of 250 nm – 2500 nm. NIST-traceable calibrated photodiodes (with a wavelength range of 300 nm – 5000 nm) provide for absolute flux measurements. CfD also has a spot projector to characterize the inter-pixel response of the detectors, including optical and electrical crosstalk. Figure 35 shows a laser spot projection system on a 3D motorized stage that produces a small (~few microns) point source for measurements of intrapixel sensitivity.

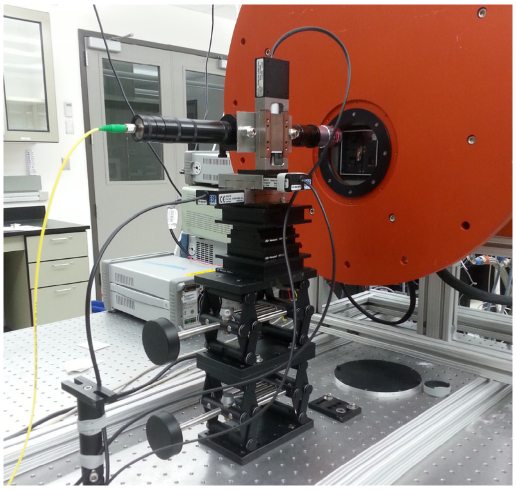


*Figure 35. A laser spot projector with three axis motion control system is used to project a small spot of light within individual pixels of detectors in order to measure the response in all regions of a pixel.*

RIDL contains seven data reduction computers, each with eight to twenty-four processors and up to 32 GB of memory for data acquisition, reduction, analysis and simulations, and 75 TB of data storage. Custom software runs an automated detector test suite of experiments. The test suite accommodates a wide variety of testing parameters through the use of parameter files. A complete test suite takes a few weeks to execute and produces ~0.5 TB of data. The data reduction computers reduce and analyze the data using custom automated code, producing publication-quality plots in near-real time as the data are taken.

In addition to the RIDL, CfD conducts research using the Lobozzo Photonics and Optical Characterization lab (Figure 36), home to the Nanophotonics Group led by CfD professor Dr. Stefan Preble. This group develops high performance nanophotonic devices and systems using Complementary metal–oxide–semiconductor compatible materials and processes. Their work will enable unprecedented performance and efficiency by leveraging the inherently high bandwidths and low power of photons with the intelligence of electronics. The group aims to demonstrate optoelectronic chips that will revolutionize future computing, communication and sensing systems.

This lab includes a Ti: Sapphire Laser, Optical Parametric Oscillator, Atomic Force Microscope, Ion Mill, Cryogenic Optoelectronic Probe Station, and Telecom test equipment. Other CfD, Microsystems Engineering faculty and students for various experiments, such as Terahertz measurements and Time-Resolved Photoluminescence, also use the lab.

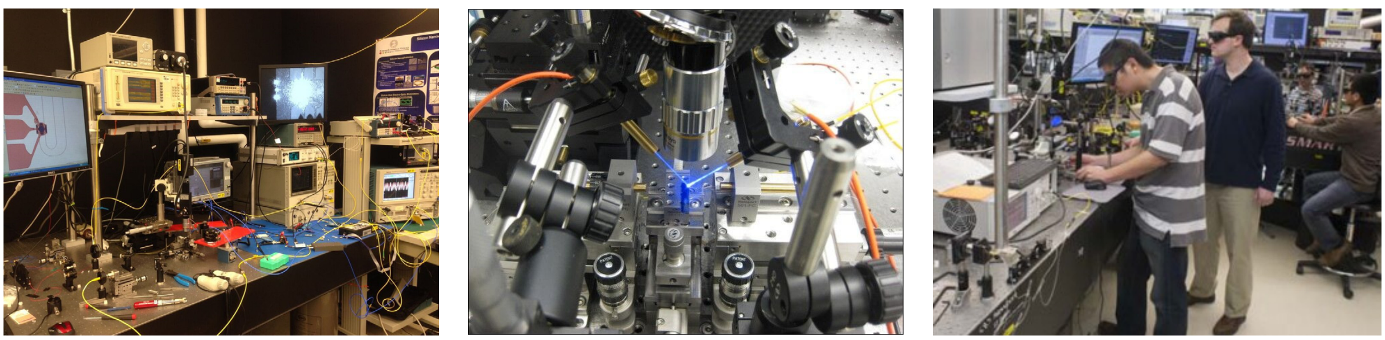


*Figure 36. Shown here are Images of the Nanophotonics lab and Professor Stefan Preble working with graduate students.*

Located within the Lobozzo laboratory is a semiconductor device optical property measurement lab, led by Dr. Jing Zhang. The laboratory contains a photoluminescence (PL) system, seen in Figure 37, including an iHR320 spectrometer, a Syncerity CCD Array detector, a Liquid Helium Cyrostat and a 325 nm HeCd laser. There is LabSpec software capable of measuring semiconductor luminescence spectrum with wavelengths ranging from 325 nm -800 nm. The liquid Helium Cyrostat enables the system to conduct measurements at temperatures as low as 4K.

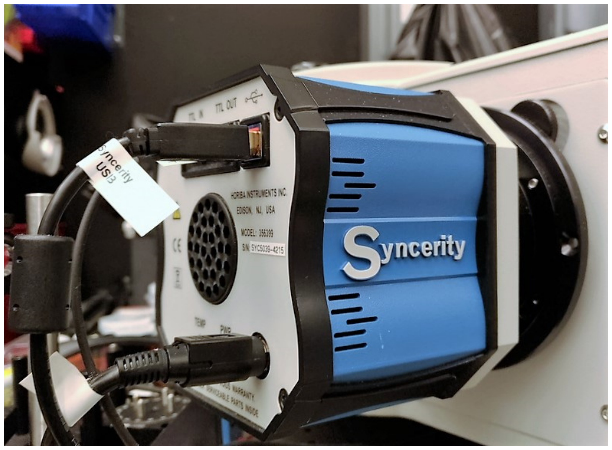
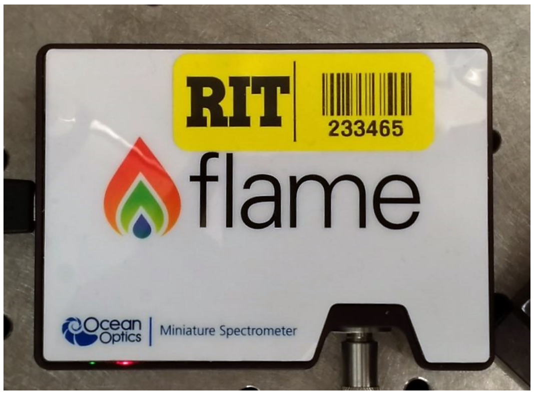




*Figure 37. The Syncerity CCD Array detector (left) and the HR320 spectrometer (right), are both integral parts of the photoluminescence system.*

The lab also includes an electroluminescence (EL) measurement setup (Figure 38) including a FLAME-S-UV-VIS-ES spectrometer (200 nm-850 nm) and a rotatable stage which enables polarization-dependent and angle-dependent measurements. In addition, an 843-R handheld Laser Power Meter was procured during last year for device power measurements.



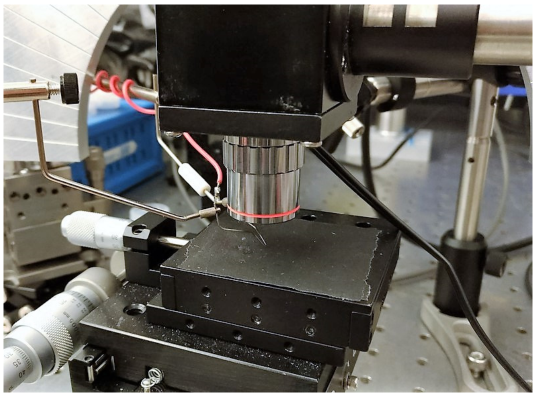



*Figure 38. Above are a FLAME 200-850 nm spectrometer (left) and the rotating testing stage (right), parts of the electroluminescence measurement setup.*

CfD collaborates with groups using the SMFL, a 10,000 ft$^2$ cleanroom space in class 1000, 100, and 10. Using the SMFL's resources, the Center can fabricate detectors with custom process flows, and has the freedom to use multiple process variations.

The Center's flow-bench and probe stations offer wafer-level testing, even during the fabrication process, allowing mid-process design changes (Figure 39). The probe station accommodates electrical and circuit analysis of both wafers and packaged parts, including low current and radio frequency (RF) probing.

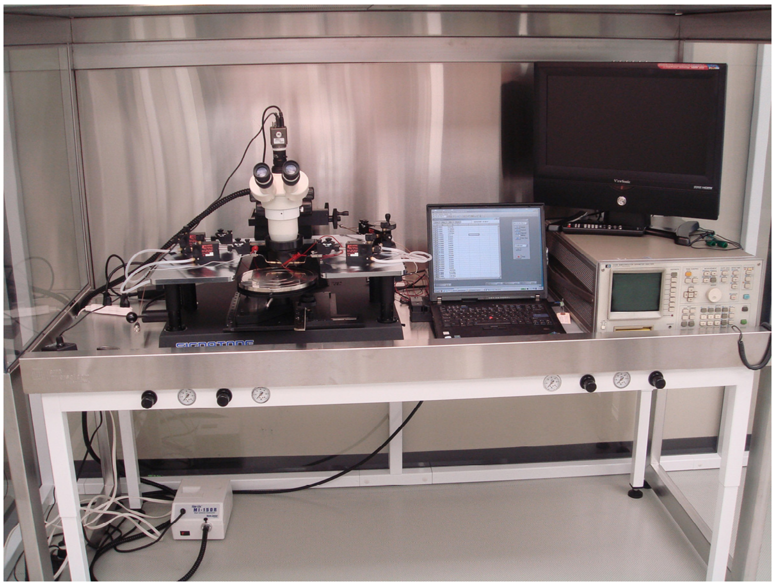


*Figure 39. Device wafers are tested in the flow-bench lab probe station.*

The Amray 1830 Scanning Electron Microscope (SEM; see Figure 40), at the SMFL is used for high-magnification imaging of devices, and the WYKO white light interferometer, used for surface topography measurements. The SMFL also has other in-line fabrication metrology capabilities, including material layer thickness, refractive index, and wafer stress characterization tools.

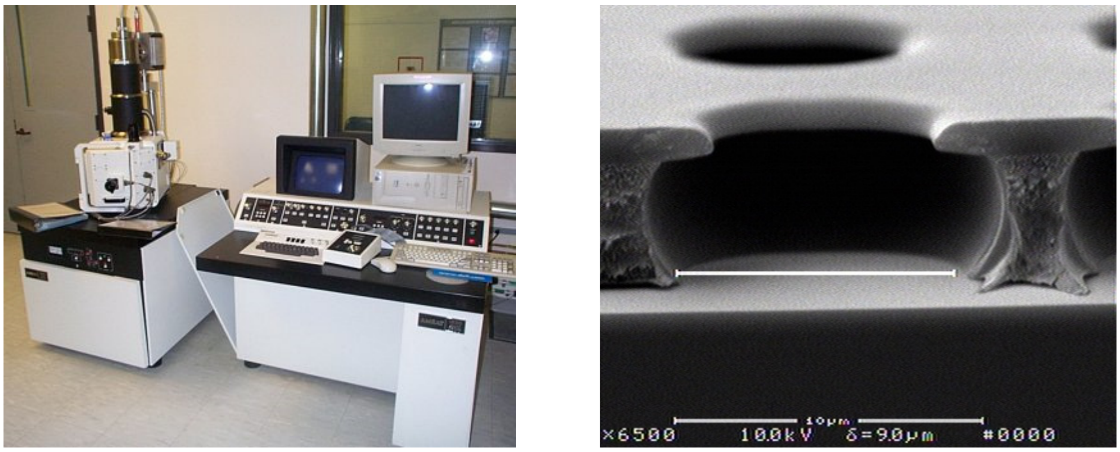



*Figure 40. (left) The Amray 1830 Scanning Electron Microscope is used to image devices. On the right, a SEM image of a device that has been prepared for indium bump deposition.*

Figure 41 shows a customized setup consisting of two voltage power supplies, an Agilent oscilloscope, an LCD screen for viewing devices through the microscope probe station, and a custom circuit board for specific device diagnostics. The dedicated lab computer also runs a specially-designed data acquisition program to collect and analyze data from the device.

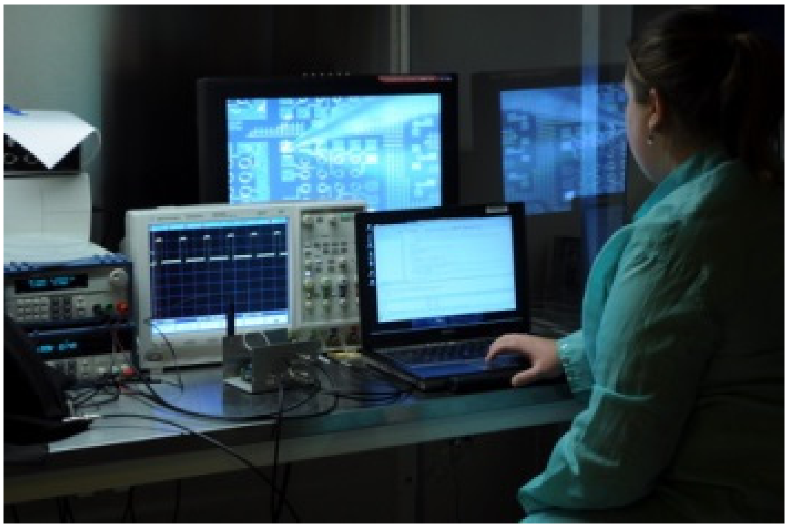


*Figure 41. Former PhD student Kimberly Kolb conducts electrical experiments on one of the innovative devices being characterized at the Center for Detectors.*

The entire probe station is covered so that no stray light enters the testing environment. These conditions provide the basis for valuable testing and data analysis. The probe tip is contacting a single test device via a metal pad with dimensions of only 70 microns by 70 microns (an area of 0.005 $mm^2$), seen in Figure 42.

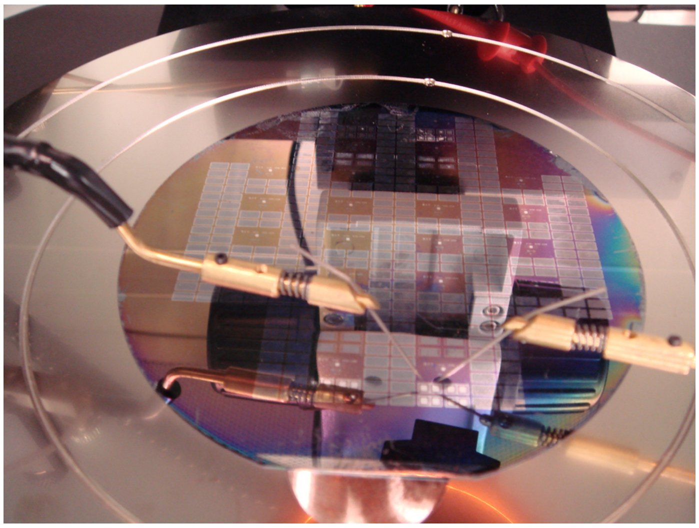


*Figure 42. This image is a close-up of a device wafer being tested on the probe station.*

In addition to fabrication and testing capabilities, the Center for Detectors has access to sophisticated simulation software to predict the performance of devices, from fabrication processes to performance of a completed device. Silvaco, Athena, and Atlas are powerful software engines that simulate the effects of processing on device substrates and the electrical characteristics of a fabricated device. Athena simulations can describe all of the processes available in the RIT SMFL, building a physics-based model in 3D space of a device from initial substrate to completed device.

The Center for Detectors uses many other RIT facilities, including the Brinkman Lab, a state-of-the-art facility for precision machining, and the Center for Electronics Manufacturing and Assembly (CEMA), a facility for electronics packaging (Figure 43).

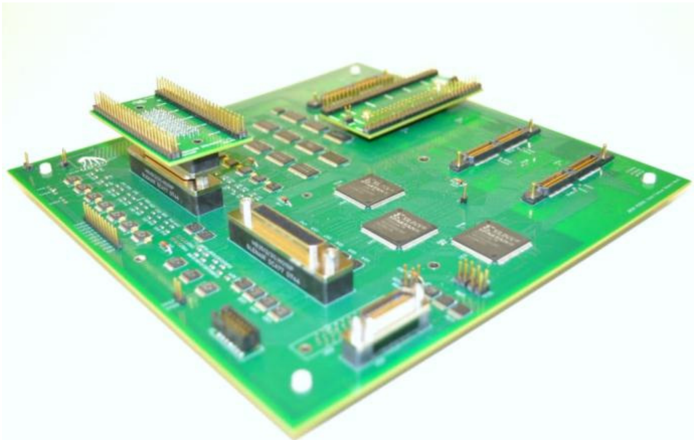


*Figure 43. This image shows a cryogenic multi-layer circuit board designed in the CfD and populated in CEMA. All of the components on this board will be exposed to temperatures as low as 40 K, nanoTorr pressure levels, and high energy particle radiation.*

Another component of the Center's facilities is the Experimental Cosmology Laboratory, directed by Michael Zemcov. This 375 $ft^2$ lab is capable of creating technologies for grounded space-based applications in experimental astrophysics. The lab has equipment to assist in creating physical components and complementary software, seen in Figure 44. The laboratory contains two Oerlikon Leybold Turbolab turbo-molecular pump systems, optical benches, lifting equipment, and tooling and component fabrication equipment. There are multiple computers capable of running sophisticated algorithms for astrophysics simulations. The lab also includes a millimeter wave spectrometric readout system for transition edge superconducting bolometers, as well as two liquid-helium cryostats and an electronic fabrication station. A new vibration test system and a rapid-prototyping PCB mill were procured during the past year. There are plans to expand the lab's capabilities in the future.



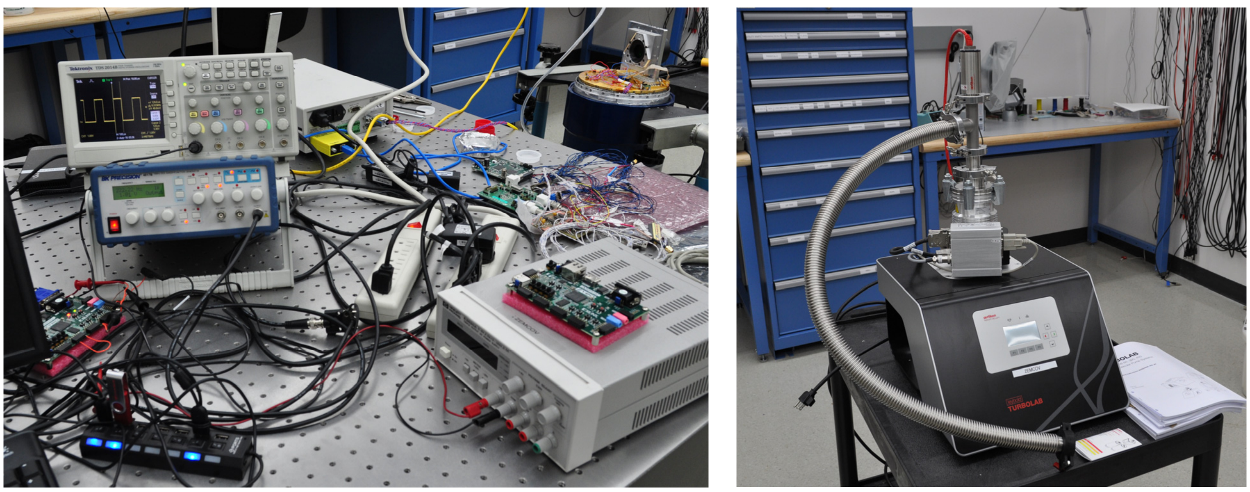


*Figure 44. (left) Pictured here are the function generators, oscilloscopes, and FPGA based control boards used to develop an image sensor readout package that will fly on a suborbital platform. On the right is one of the Oerlikon Leybold Turbolab turbo-molecular pumping stations employed by the lab.*

The Center for Detectors also employs the capabilities of the Epitaxially-Integrated Nanoscale Systems Laboratory (EINSL), under the direction of Dr. Parsian Mohseni. This lab, part of RIT's Nanopower Research Laboratory (NPRL), focuses on atomic-level semiconductor assembly and metalorganic chemical vapor deposition (MOCVD). The lab develops devices used for photovoltaics, optoelectronics, and nanoelectronics. Their research finds real-world applications in solar energy, solid-state lighting, and lasing. Current research areas in the EINSL include metal-assisted chemical etching of semiconductors using non-conventional catalysts, multi-junction III-V nanowire on silicon solar cells, and GaAsP/GaP nanowire white light LED's.

Researchers in the EINSL have access to the wide range of capabilities provided by the NPRL, seen in Figure 45, which include a Perkin Elmer Lamda 900 UV-Vis-NIR optical spectrometer and a metal organic vapor phase epitaxy (MOVPE). NPRL also has multiple advanced microscopic imaging systems, including a Nikon Eclipse Digital Nomarski microscope, Hitachi S-900 High Resolution Near Field FE-SEM, and Zeiss Digital Microscopic Imaging System.


*Figure 45. (left) Ph.D.student Mohad Baboli loads a sample in the AIXTRON 3×2 Close Coupled Showerhead metal-organic chemical vapor deposition reactor, part of the MOVPE. (right) PhD student Thomas Wilhelm uses a TESCAN MIRA3 scanning electron microscope to analyze samples for use in metal-assisted chemical etching experiments.*

The Center also conducts research using the Laboratory for Advanced Instrumentation Research (LAIR). The LAIR focuses on the development of instruments for gathering data from a wide range of physical phenomena.

Along with collaborators at the University of Rochester and Harris Co., the LAIR is developing a Terahertz (THz) imaging detector using Si-MOSFET CMOS technology, shown in Figure 46. Researchers are parametrically testing individual devices with different variations to optimize the THz response. The optimized design will then be implemented into a large focal plane array for many different applications, including security, medical imaging, and remote sensing.

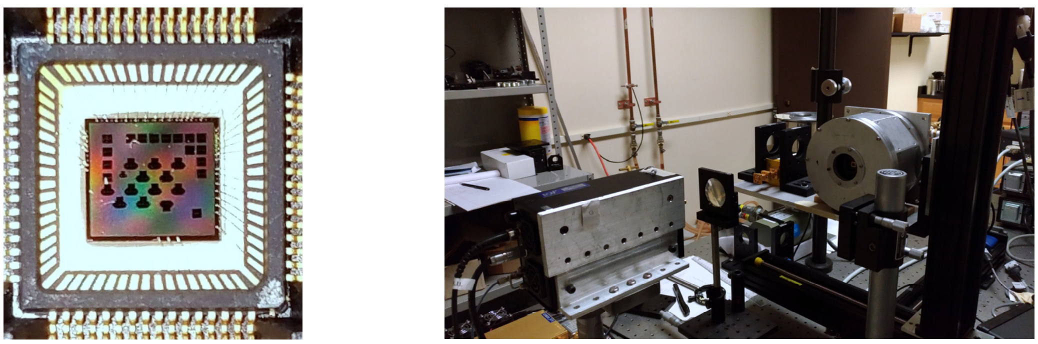


*Figure 46. Student researchers at the LAIR developed the terahertz detector pictured above. The detector uses metal-oxide semiconductor field-effect transistors to conduct transmissions of terahertz measurements.*

Research at the LAIR has been funded by NASA, the NSF, NYSTAR and a variety of corporations such as ITT, Kodak and ThermoFisher Scientific.