THE CLAIRE AND JOHN BERTUCCI NANOTECHNOLOGY LABORATORY AT CARNEGIE MELLON UNIVERSITY

A PREMIER NANO-MAKER HUB

Carnegie Mellon University
College of Engineering

The Claire and John Bertucci Nanotechnology Laboratory is a premier nano-manufacturing hub dedicated to the invention and demonstration of micro- and nano-systems. Our mission is to provide best-in-class services and high-tech equipment to innovative nano-makers. To deliver this, the “Nanofab” houses approximately 100 processing tools in a 14,000-square-foot nanofabrication research facility located in Carnegie Mellon University’s Sherman and Joyce Bowie Scott Hall.

At the center of the Bertucci Nanotechnology Laboratory is the brand-new 8,500-square-foot Class 10/100 Eden Hall Foundation Cleanroom. Characterized as one of the most energy-efficient cleanrooms in the United States—more than three times as efficient as many cleanrooms of similar size and class—this facility has helped Scott Hall earn the distinction of being certified LEED Gold by the U.S. Green Building Council.

In addition to the cleanroom, the facility includes a post-processing lab, tool development space, and offices for our highly-qualified technical staff. Furthermore, the lab features state-of-the-art controls, 19 brand-new wet chemistry decks, three EMI-shielded rooms, and many other advanced features designed to support a continuously growing and diversified set of users and more than $10 million per year in cutting-edge research.

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Nano-maker ecosystem

Our nano-maker ecosystem is a space, philosophy, and methodology that enables rapid prototyping of nanoscale devices, engagement with industry and university affiliates, incubation for start-ups, and education and outreach activities.

Carnegie Mellon is one of the few places that facilitates a maker culture at the nanoscale, allowing researchers to use our facility to shape new materials into emerging and novel technologies. Resources for rapid prototyping of nanoscale devices include support for users with layout and fabrication of simple and complex structures, as well as access to both cutting-edge equipment and a material and process database.

Our engagement with industry and university affiliates involves collaboration and partnership with local and national organizations, connections with graduate students, and a regional community of users that shares common practices. We also support the start-up incubation development process for Carnegie Mellon-based and local start-ups. In the future, we plan to offer boot camps for the rapid training of industry partners and students.

In addition, we provide education and outreach initiatives, including technical seminars for professional Nanofab users and industry collaborators, student courses that offer hands-on training in nanofabrication, and outreach programs to high school students and teachers.

A history of collaboration

Carnegie Mellon has been pursuing research at the nanoscale since the early 1980s. Research in micro- and nanoscale magnetics enabled the creation of the first nanofabrication facility on campus. This original nanofab has been transformed into a collaborative space for faculty from different departments and disciplines to work together to build micro- and nanoscale devices.

Over time, the Nanofab has evolved to better facilitate this collaborative research, especially by augmenting tools and capabilities. These enhancements paved the way for the creation of the state-of-the-art Bertucci Nanotechnology Laboratory, a space that enables and leverages campus-wide collaborations and broader research thrust areas.

1980s

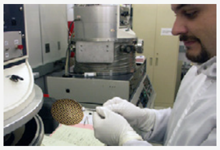
- The initial Nanofab was established in 1983, launched by magnetics work, its key focus.

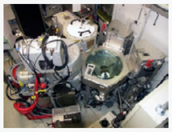
1990s

- The Nanofab remained heavily focused on magnetics [as the Data Storage Systems Center (DSSC), an NSF ERC, was created at CMU] but began to expand capabilities for MEMS in the mid- to late-1990s.
- In 1996, Roberts Engineering Hall was built with new rooms to accommodate expanding research.
- Several major equipment and facility acquisitions occurred in 1998.

2000s

- The Nanofab's focus became broader to include optics and photonics. Hard drive advancements began to taper off while new storage and memory technologies began to emerge.
- The MEMS effort began to ramp up and became a major focus as lots of new equipment was added.





2010s

- Planning for the new lab kicked off during this decade while faculty in biomedical engineering, materials science and engineering, and mechanical engineering began using the Nanofab more, initiating a shift toward a broader and more collaborative research effort on energy, life sciences, and Internet of Things.
- More than a dozen new pieces of major equipment were acquired during this time frame in an effort to meet more modern needs and increased collaboration, as well as to keep the lab state-of-the-art.
- In 2017 the new facility opened. Equipment started to move in, and the space was opened to research. Full occupancy is expected in early 2019.

RESEARCH APPLICATION THRUSTS

Carnegie Mellon leads the world in multiple areas of nanofabrication research: magnetics and spintronics; MEMS and NEMS; functional oxides and resistive RAM; photonics and plasmonics; microrobotics; biointerfaces and bioelectronics; and 2D materials. More than 40 Carnegie Mellon faculty members use the nanotechnology laboratory to pursue these lines of research.

The multidisciplinary and collaborative nature of our faculty has given rise to several major research thrusts centered around nanoscale manufacturing. Micro- and nanofabrication are used in the following application areas.

EMERGING COMPUTING TECHNOLOGY

Research is focused on non-volatile memories, magnetic logic, nanoelectromechanical relays, and quantum devices

INTERNET OF THINGS

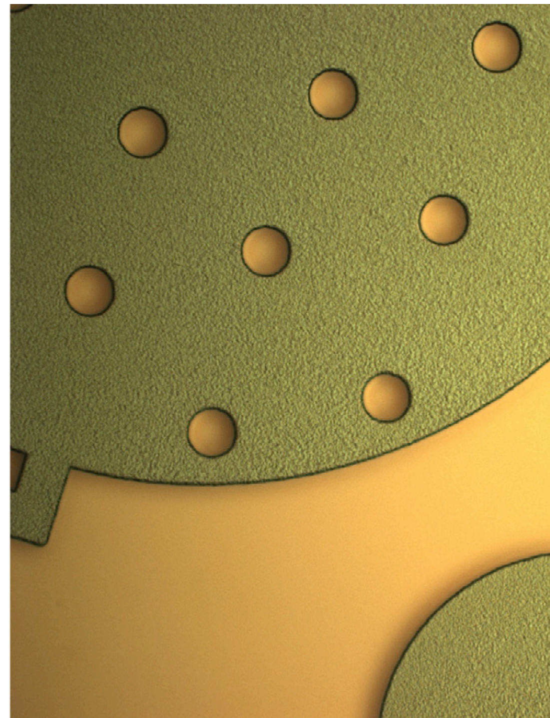
Research is focused on advanced integrated sensors, actuators, resonators, modulators, and switches

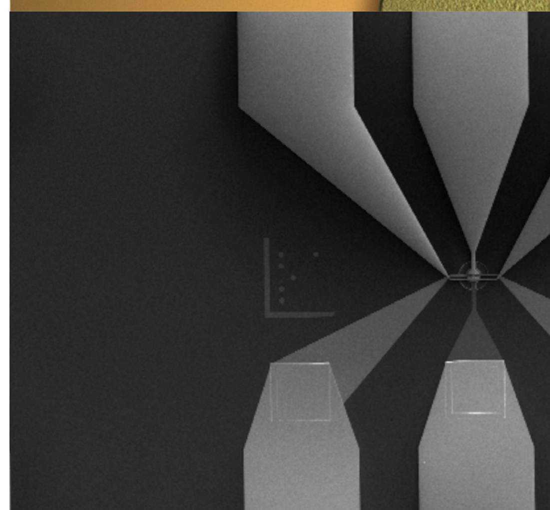
ENERGY

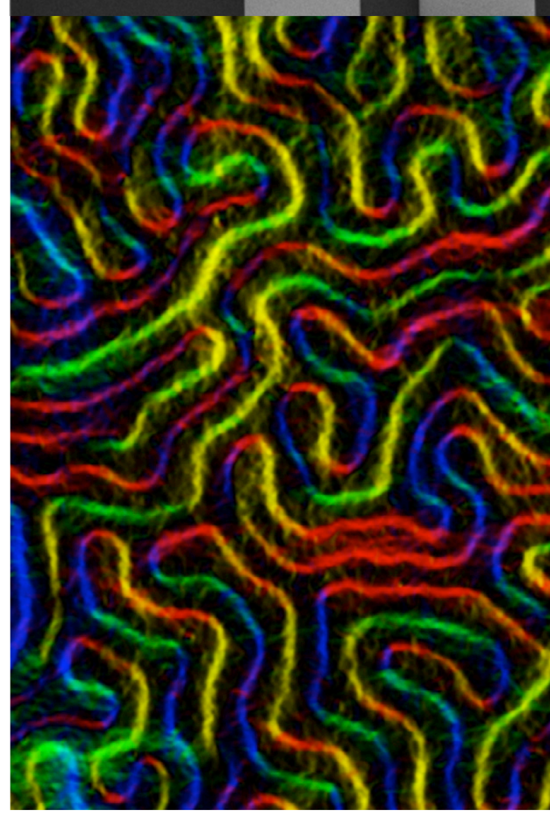
Research is focused on solar and thermal adsorbers, materials for energy conversion, light harvesting materials, and thermal management technology

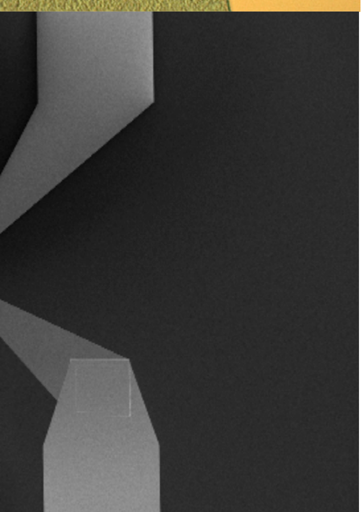
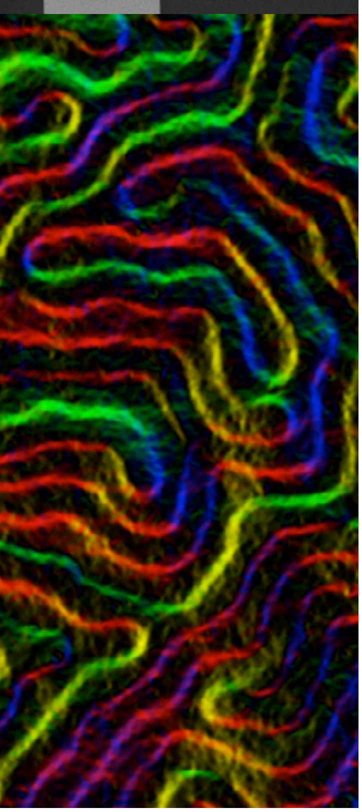
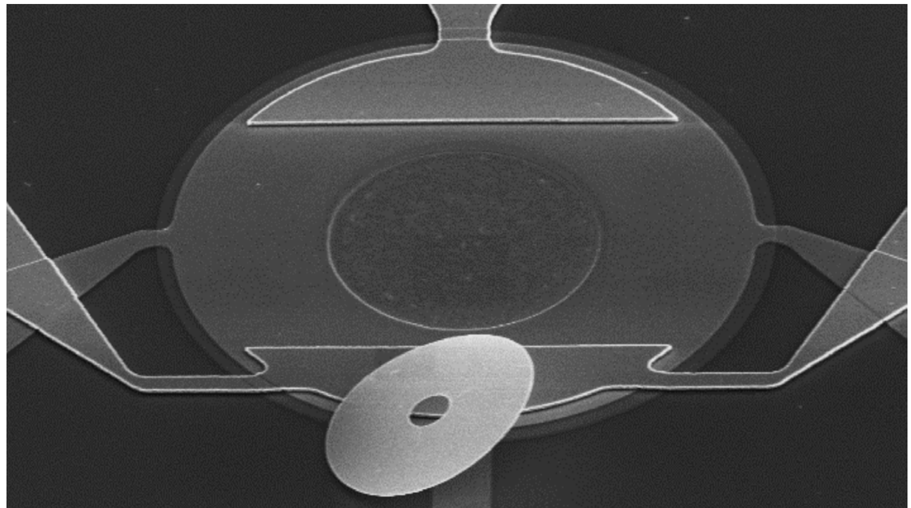
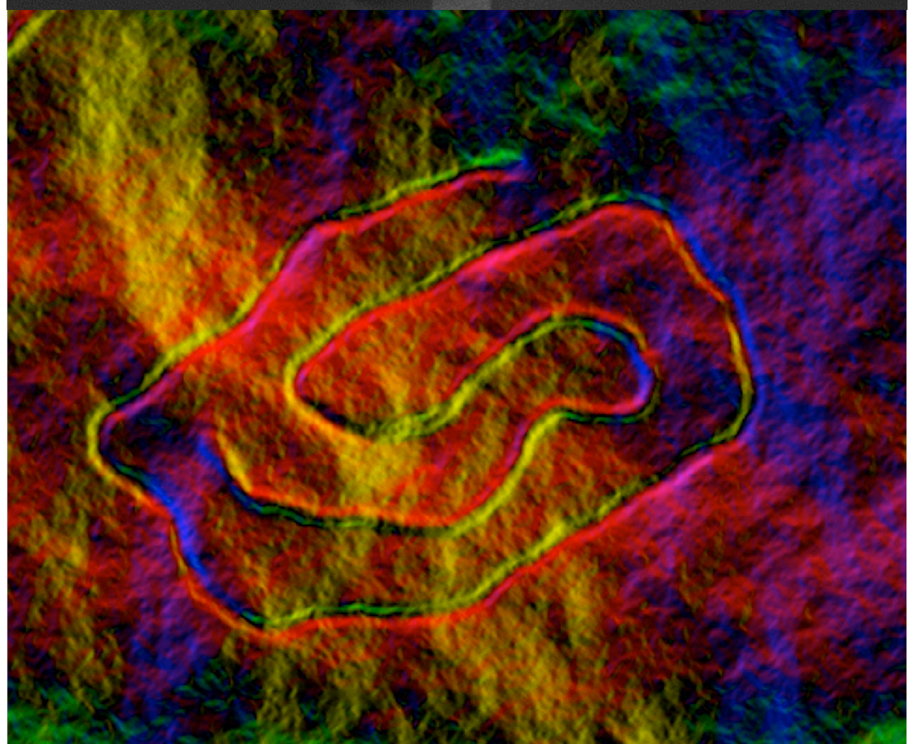
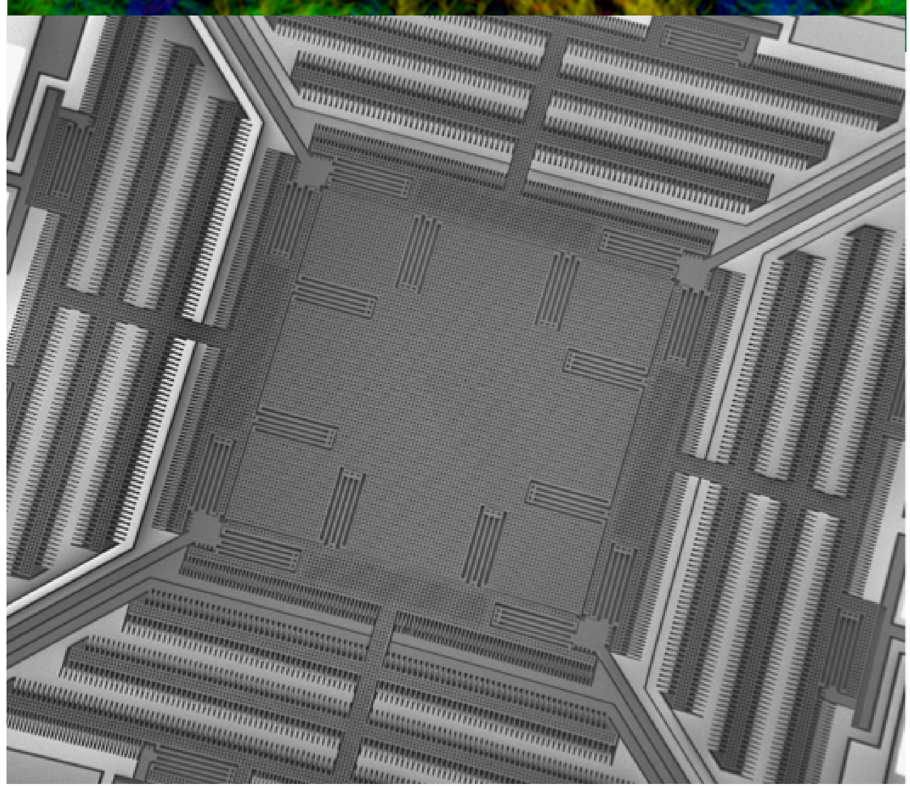
LIFE SCIENCES

Research is focused on neural probes, bio-sensors, hydrogel electronics, and protein scaffolds







EMERGING COMPUTING TECHNOLOGY

Research and development in the semiconductor industry has long been driven by Moore's Law, the observation and prediction of Intel Founder Gordon Moore in 1965 that the number of transistors in a dense integrated circuit doubles about every two years. For decades, advances in computing have been fueled by exponential decreases in power consumption and in relative cost, leading to ever faster, smaller, and cheaper transistors that enable today's ubiquitous computing and electronics.

At present, a number of compounding factors are converging to limit the future viability of traditional transistor technology. The end of the days of Moore's Law and the difficulty in dissipating thermal energy created by increasingly densely packed electronics has the tech industry scraping the upper limit of its ability to maintain advances in transistors apace with societal demands. Perhaps more importantly, our visions for a connected world proliferated with sensor networks serving a vast and diverse host of functions has generated a need for low-energy electronics that traditional transistors simply cannot meet alone.

TOPICS

- MLOGIC – SPIN-BASED LOGIC
- CHIRAL MAGNETISM
- NANOSCALE OXIDE OSCILLATORS
- NANOFABRICATED MTJS
- RERAM SWITCHING BEHAVIOR
- NEMS RELAYS
- PHASE CHANGE MATERIALS
- QUANTUM PHOTONIC CIRCUITS

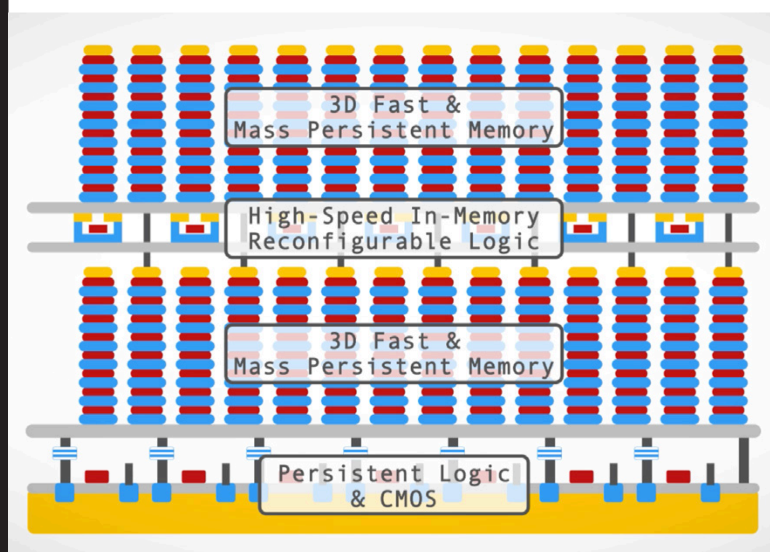
APPLICATIONS

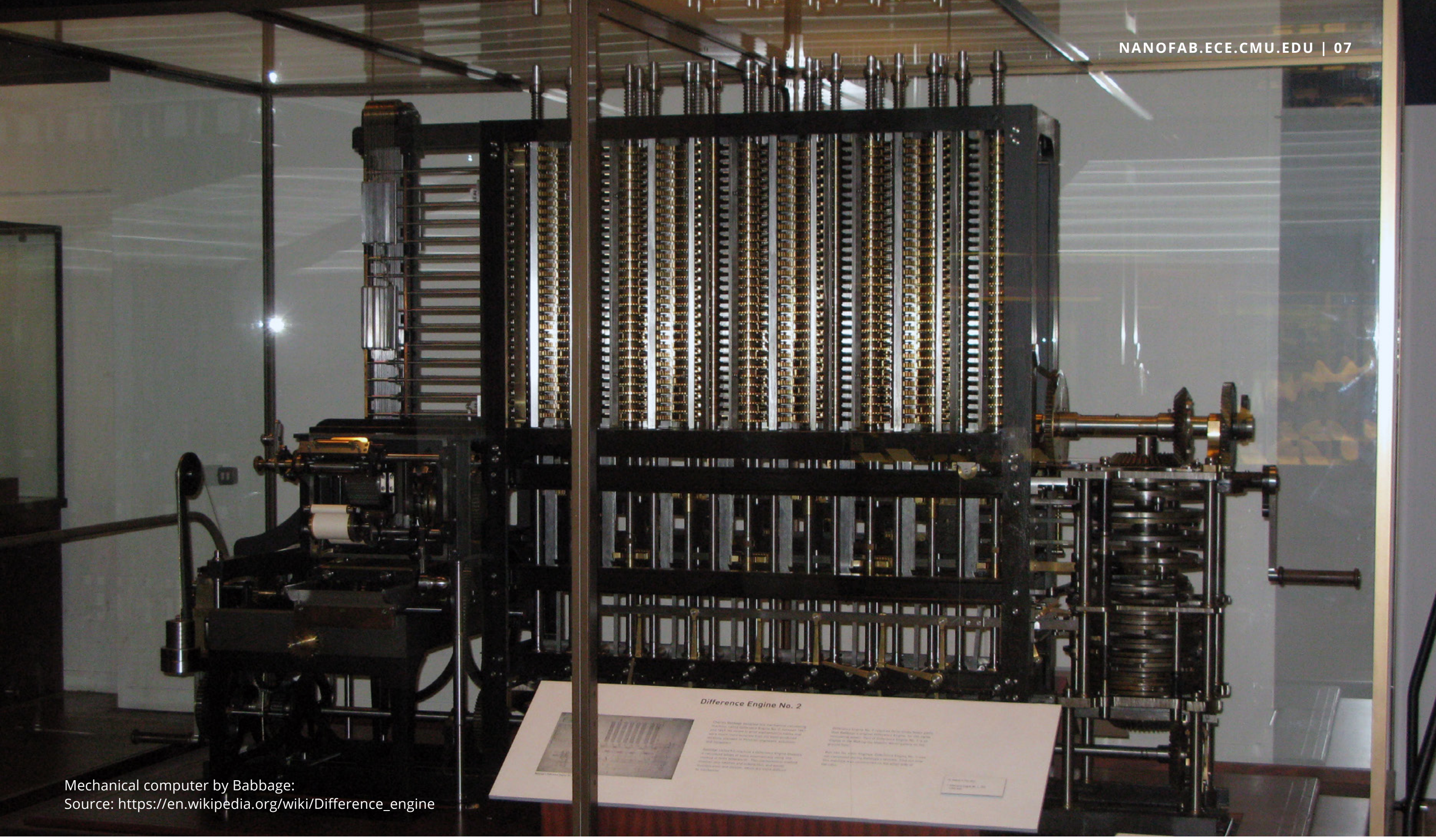
- COMPUTING WITH SCAVENGED ENERGY
- NEUROMORPHIC COMPUTING
- QUANTUM INFORMATION SCIENCE

REMANENCE COMPUTING

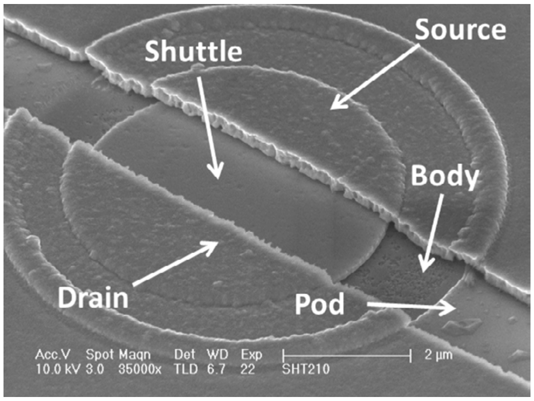
Today's computer hardware platform limits the advancement of fields such as artificial intelligence. Currently, logic, memory, and data are all separate entities within the computer architecture. In addition, there is a gap between the performance of computing power—which has been increasing at about 60% per year for the last two decades—and the performance of memory—which has only been improving at rate of 7% per year. These factors combine to create a situation where processors end up wasting power while waiting for data.

To address this, faculty in the Nanofab are working on a new computing platform called remanence computing that fuses logic, memory, and data together on a single chip. Integrating non-volatile memory directly with the logic circuits enables data-centric computing at significantly higher speeds and lower power and opens the door to truly pervasive artificial intelligence.

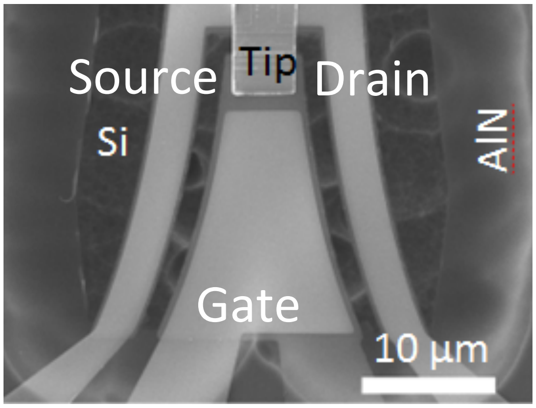




Mechanical computer by Babbage:
Source: https://en.wikipedia.org/wiki/Difference_engine



Pulsed Activated Piezoelectric Switch (PAPS)



Triple-Beam Piezoelectric NEMS Relay

PIEZOELECTRIC NANOELECTROMECHANICAL RELAYS

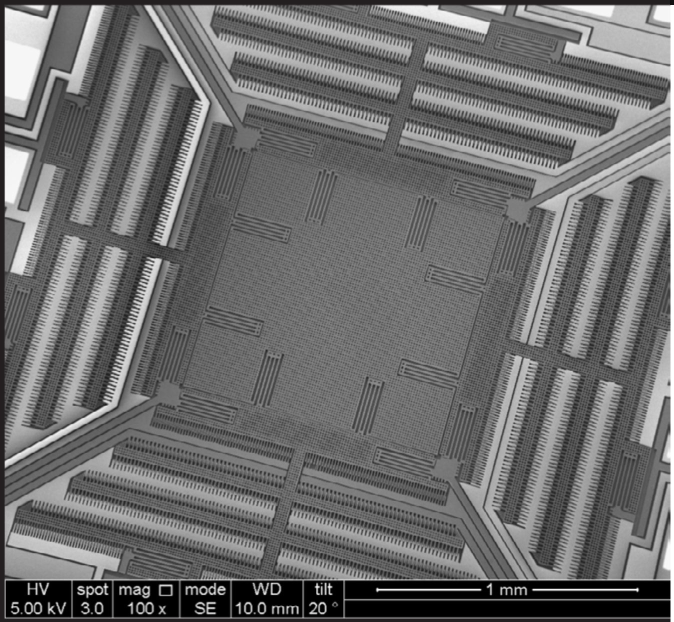
Another example of work in this area focuses on the development of a new form of switch called the piezoelectric nanoelectromechanical relay. This device could be the key to replacing semiconductor transistors in many applications. These relays utilize mechanical energy—rather than changes in electronic characteristics, like transistors—to initiate a change in state. They also exhibit lower current leakage, cutting both energy usage and excess heat.

These two combined characteristics mean that devices utilizing these relays could potentially consume less energy than traditional electronics by multiple orders of magnitude. The relays' low-energy demands mean that embedded sensors and implants may not necessarily require a battery and could instead harvest the small amount of energy they require from the environment around them or from the body, respectively.

With the last half a century of computing architecture design having been driven by Moore's Law and built around the traditional semiconductor transistor, the long-term effects of these developments are poised to revolutionize the field of computing.

INTERNET OF THINGS

The Internet of Things (IoT) is the sphere of technology that enables everyday devices—such as the thermostat in your house or the fitness tracker on your wrist—to receive, collect, and transmit data via the internet. The IoT is developing into an interconnected network of trillions of sensors that monitor everything from your body to your car to the environment.



MEMS AND NEMS

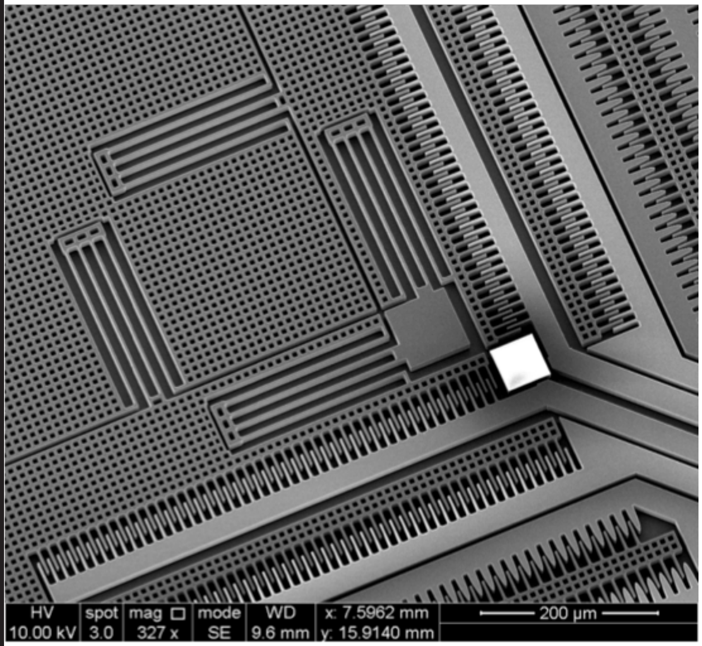
One class of low-power sensors we are building is micro- and nano-electromechanical systems (MEMS and NEMS). These systems use miniaturized mechanical devices built with conventional semiconductor tools to perform highly sensitive functions. For example, we are developing accelerometers and gyroscopes that will enable high precision navigation and geolocation when GPS signal is not available. In addition, we are developing MEMS devices for low-power radios to enable trillions of sensors to communicate with each other without ever needing a new battery. These sensors can detect an incredibly small radio frequency signal with almost no power and wake up a more power-hungry radio only when needed, effectively reducing energy waste.

TOPICS

- PHASE CHANGE RF SWITCHES
- NANOSPLAMONIC FOCUSING STRUCTURES
- CMOS-MEMS ACCELEROMETERS AND RESONATORS
- ACOUSTO-OPTIC MODULATORS AND FILTERS
- MEMS RESONATORS, FILTERS AND GYROSCOPES

APPLICATIONS

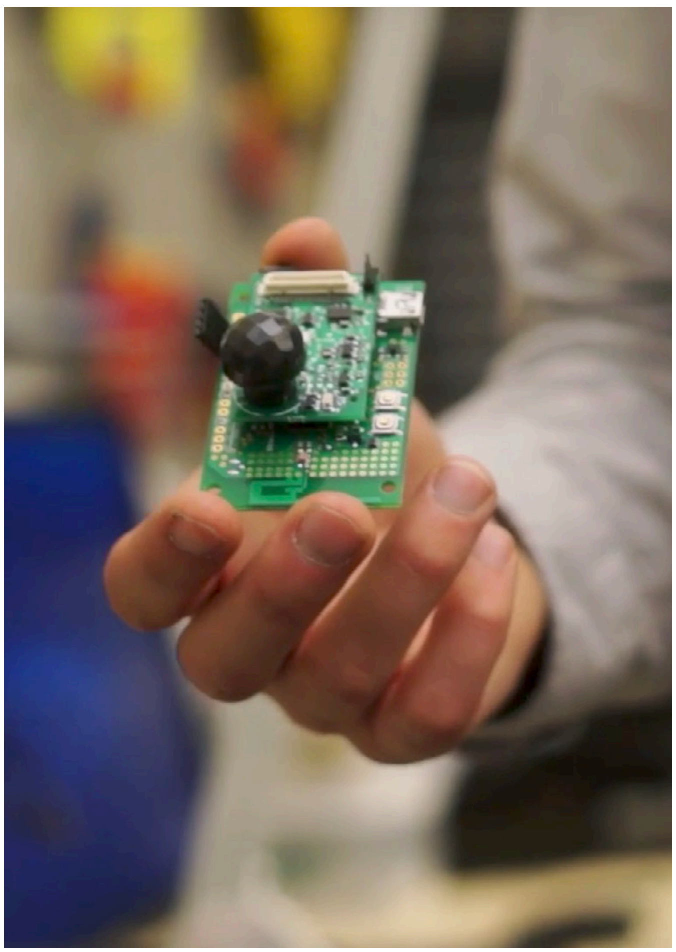
- MOBILE/SATELLITE COMMUNICATIONS
- WAKE-UP RECEIVERS
- SENSOR NETWORKS
- INERTIAL SENSING



WIDELY-DISTRIBUTED SENSORS

IoT devices can enable personal applications—such as tracking your heart rate, steps, and sleep—or have more wide-reaching uses. These devices can monitor a building to adjust temperature and lighting based on occupants, or an entire city could use sensors to identify critical infrastructure that needs repair before disastrous failures occur.

Successful implementation of distributed sensor networks requires tiny sensors that operate on minimal power. Widely-distributed sensors—across a building, a city or space—will not be successful if they disrupt everyday activities or constantly need new batteries. In the Nanofab, we are pursuing the development of tiny, energy-efficient, and self-powered sensors and devices.



SELF-REPROGRAMMING SENSORS

One challenge with communication links is that they have to last in the field a long time despite changes to standards and protocols. We are working on small-scale devices that can self-reprogram and thus do not need to be replaced when standards change.

These and other advances will help realize the promise of the Internet of Things as Carnegie Mellon researchers shape and define the future of IoT devices through their work.

ENERGY

Since humans' earliest days on the planet, using and harnessing energy has been key to our survival and our ability to thrive. Today, our sheer numbers combined with our modern, energy-intensive lives are making our energy needs and challenges more intense and pressing than ever.

To overcome these challenges we will require novel approaches. In the Nanofab, we are working on key issues in energy generation, conversion, and storage to reduce power consumption and enhance the energy-efficiency of devices. We exploit unique material properties at the nanoscale or pattern nanoscale features that improve the efficiency of a device or material.

TOPICS

- NANOPHOTONIC SOLAR ABSORBER
- MICRO THERMAL DEVICES
- NANOSCALE THERMAL INTERFACES
- MECHANO-CHEMICAL ACTUATION
- CONTACT MATERIALS FOR MECHANICAL RELAYS
- LIGHT-HARVESTING NANOMATERIALS

APPLICATIONS

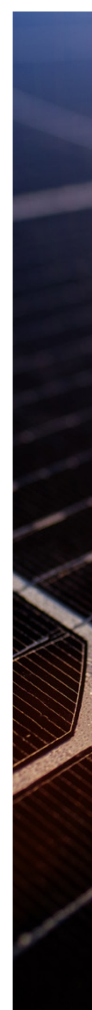
- THERMAL MANAGEMENT
- SOLAR ENERGY CONVERSION
- STRONGER MATERIALS

IMPROVED BATTERY LIFETIMES

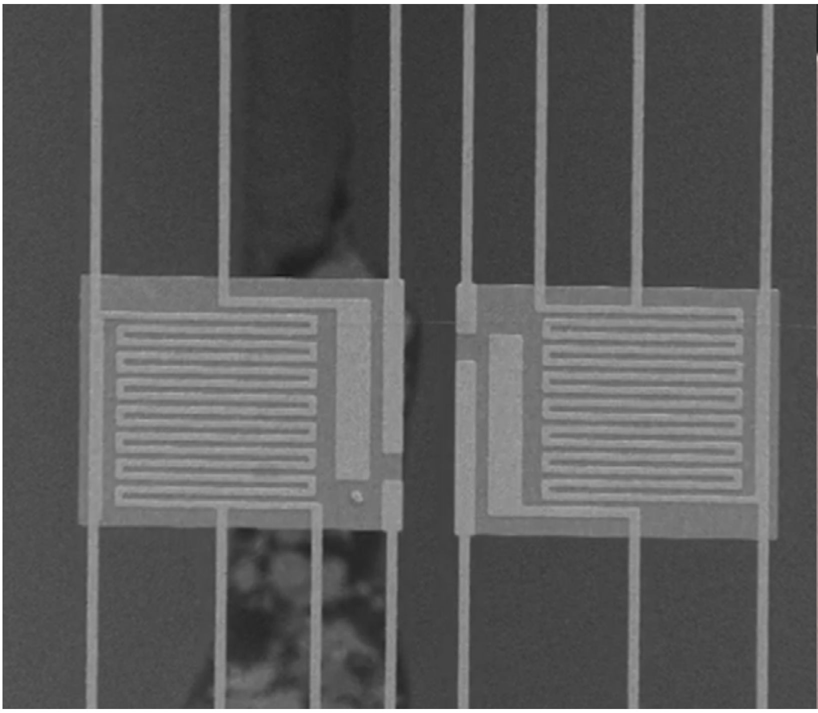
Another way to advance energy technology is to improve battery lifetime. We are investigating the role of hybrid polymeric films as interface modifiers in energy storage, including battery applications. Our aim is to formulate a fundamental understanding of charge and heat transfer processes at organic-inorganic heterojunctions, which is key for improving operational efficiency and stability.

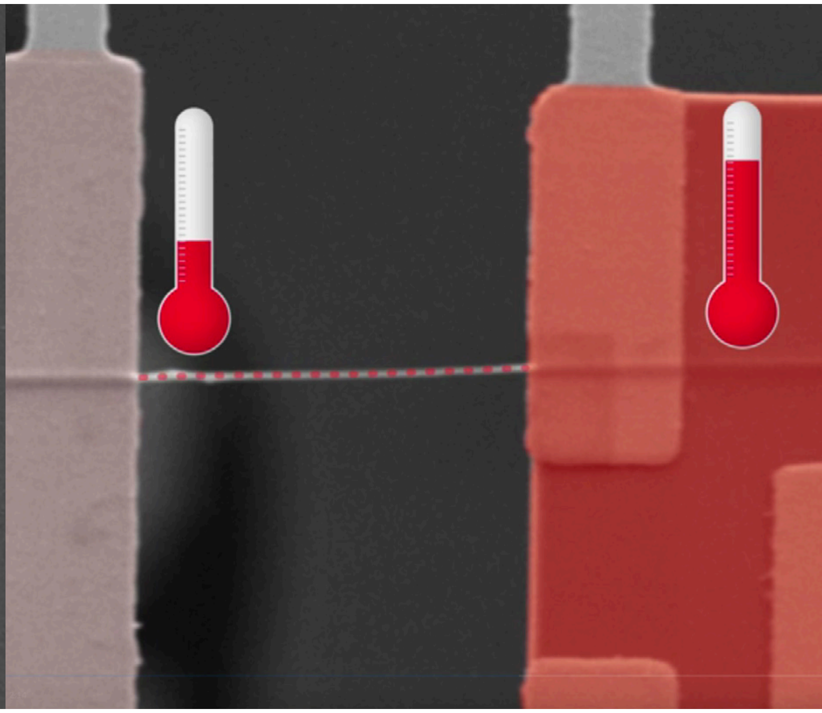
These are just a few examples of how we can address our current and future energy needs. Such advances will be necessary to enable continued innovation and ensure we respond to the growing demand for energy while preserving the environment.

AMBIENT ENERGY HARVESTING



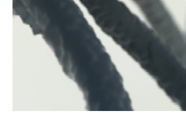
One way to reduce energy waste is to harvest energy from heat or light, utilizing otherwise wasted thermal energy from sources like the ambient environment, your car engine, or even from your body. One example of such a technology we are developing at CMU is the nanophotonic solar absorber that allows solar panels to absorb more sunlight than is currently possible. This would enable far more energy to be collected from the same number and area of solar panels, drastically improving efficiency and form factor of solar panels.





POLYMER NANOWIRES TO DISSIPATE HEAT

We are also exploring ways to improve energy-efficiency by more quickly dissipating the heat generated by devices, such as through the use of polymer nanowires. In their bulk form, polymers cannot transfer heat efficiently because they are made from long chain molecules that are random in their bulk form. However, researchers in the Nanofab are experimenting with drawing and aligning the molecules in polymers to give them a high thermal conductivity and make them far stronger. These drawn polymer nanowires have the potential for use in electronic equipment and other applications to help dissipate heat quickly and easily.



LIFE SCIENCES

Nanofab researchers aim to improve human health by using engineering to learn more about the human body and how to interact with it. The nervous system, for example, is loaded with encoded information: thoughts, emotions, motor control. This system in our bodies is an enigma, and the more we can do to understand it, the more we can do to improve human life.

Specifically, we want to be able to see what is going on inside the brain, such as to see what has gone wrong in the case of injury or disease, and then be able to affect or treat it. To do this, we need improved ways to sense the brain and then stimulate it. Several areas of research in the Nanofab are focused on understanding and treating the brain and nervous system.

TOPICS

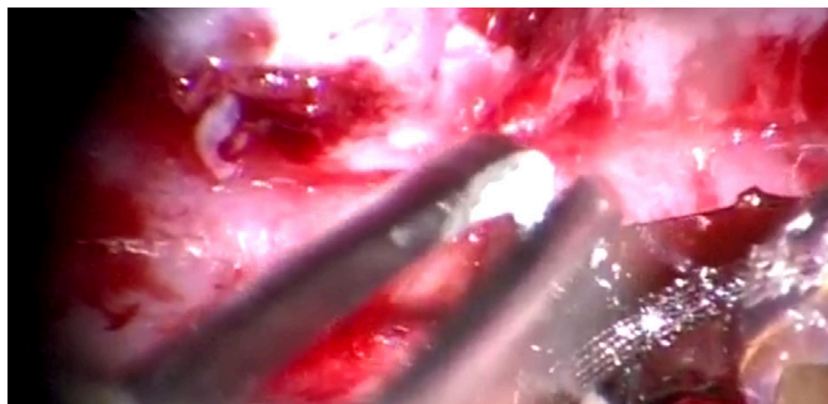
- HYDROGEL-BASED ELECTRONICS
- SELF-ROLLING 3D CHIPS
- NANOSCALE PROBES FOR NEURAL RECORDING
- PROTEIN NANOFIBER SCAFFOLDS FOR ENGINEERING CELL AND TISSUE GROWTH

APPLICATIONS

- NEURAL INTERFACES
- SMART PROSTHESES
- TISSUE REGENERATION

BRAIN SENSING AND STIMULATION

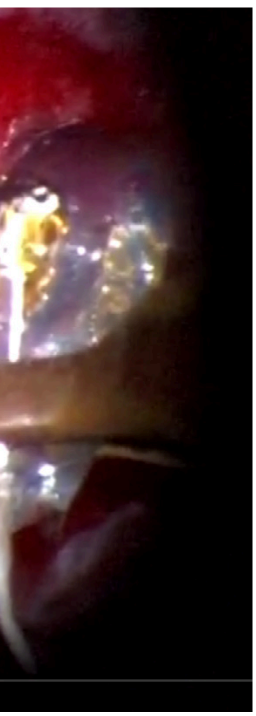
Researchers are collaborating to find novel ways to attain higher resolution from different electrode designs placed inside the brain. Fundamental laws of physics and biology have limited advances in this area to date. Our researchers are working to harness what physics offers us, as well as the complexities of biological systems to improve the spatial and temporal resolution of the sensing and stimulation of the brain.



HYDROGEL-BASED ELECTRONICS

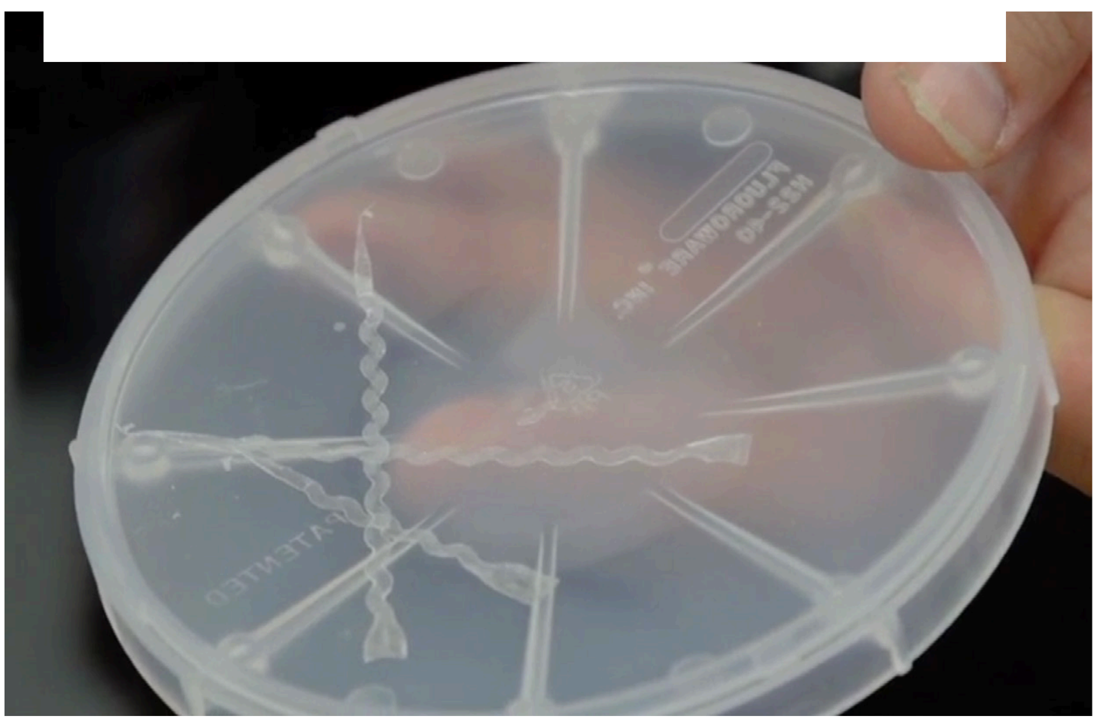
New materials can bring to bear novel solutions to seamlessly meld synthetic electronic devices with the human body. Nanofab researchers are working on polymers that will enable medical devices to be integrated with the human body. These devices allow us to record signals from the brain or other parts of the nervous system, as well as stimulate tissues to control disease states or evoke new therapeutic responses. Hydrogel-based electronics are a new class of soft electronics that can better match the properties of the brain to enable these brain-machine interfaces. By designing devices that can seamlessly merge with the peripheral nerves, we can stimulate them and record from them, and we can understand and alter disease states.

These and other technologies have the potential to transform our understanding of disease states, as well as open up new kinds of methodologies to alter those disease states and improve and extend human life.



ELECTROPHARMACEUTICS

The human body has amazing systems that produce chemicals to regulate body functions or even help us fight off or heal from various diseases. Electropharmaceutics is an area of research that uses minimally-invasive neural probes to stimulate these systems to help the body provide its own disease therapy or pain relief. In the Nanofab, researchers have developed very thin, compliant probes for electropharmaceutics that last for decades in the body.



Nanofab capabilities

The Claire and John Bertucci Nanotechnology Laboratory is a premier research facility in Western Pennsylvania and the "Tech-Belt" (PA-OH-WV) region. Located in Carnegie Mellon University's Sherman and Joyce Bowie Scott Hall, the Nanotechnology Laboratory, or Nanofab, is a 14,000-square-foot, self-supporting, open, and shared research facility that provides a wide range of tools, processes, and research space to more than 200 internal and external users from a variety of engineering and science disciplines.

The Nanofab provides as many as 100 processing tools to the community, all of which are supported through user fees, with new acquisitions supplemented by internal university funds and research grants from faculty. Researchers using the Nanofab can rely on six technical staff members to guide them by providing hands-on experience, helping them choose the best tools and processes for their research. Staff members also assist with tool training, process development, tool maintenance, and tool repair, providing expertise in lithography, film deposition, etching, metrology, annealing, and more.

Etching

- suite of 6 RIE and ICP RIE tools (supporting Ar, O_2, CHF_3, CF_4, C_4F_8, SF_6, Cl_2, BCl_3 and CH_3OH gas chemistries)
- 3 ion beam etch tools (one with SIMS endpoint)
- XeF_2 etcher
- vapor HF etcher
- wet etching stations (for solvents, acids, and bases)
- critical point dryer
- O_2 plasma asher
- UV ozone cleaner

Lithography

- 3 electron-beam lithography systems
- i-line stepper
- suite of mask aligners
- direct write laser system and photomask generator

Deposition

- suite of 15 PVD systems (sputtering, electron beam evaporation, and thermal evaporation for metals, oxides, nitrides, and semiconductors)
- ALD for metals and oxides
- PECVD for oxide and nitride
- 2 CVDs for polymer based applications
- parylene (type N and type C)
- electroplating for Cu and Ni

Post-processing, inspection, and metrology

- CMP
- stress measurement
- reflectometry
- scanning electron microscopy
- profilometry
- electrical and mechanical probe stations
- optical microscopes
- RTA
- annealing
- wafer dicing

Material capabilities (>100 available)

- variety of metals, oxides, nitrides, and semiconductors
- polymers
- parylene
- PDMS
- SU8
- Specialties include:
  - AIN
  - magnetic materials
  - functional oxides

Key tools

- Elionix ELS-G100 e-beam lithography system
- ASML 5500/80 i-line stepper
- Plasma Therm Versaline Cl-based ICP RIE
- STS Multiplex Bosch etcher
- STS Aspect AOE and ICP RIE (separate chambers)
- GVD Corp. iLab and oLab CVDs
- Tegal AMS AIN sputtering system
- Cambridge Fiji ALD with plasma
- Kurt Lesker 8-source PVD75 e-beam evaporator
- Custom-Built 5-Target Sputtering Systems for Magnetics
- CVC Connexion 6-Target Production Level Sputtering System

Join the Claire and John Bertucci Nanotechnology Laboratory

The Claire and John Bertucci Nanotechnology Laboratory is open to external users from corporate, government, and university affiliates. Approximately 200 individual researchers take advantage of the facility each year. Contracts are available for partners interested in using our lab directly, as well as those who seek fee-for-service work. Included in the contract, researchers are provided:

- 24/7 access to equipment and facilities
- tool support and training
- access to and support from knowledgeable technical staff
- access to process knowledge and recipes
- networking opportunities with students, postdocs, faculty, and staff

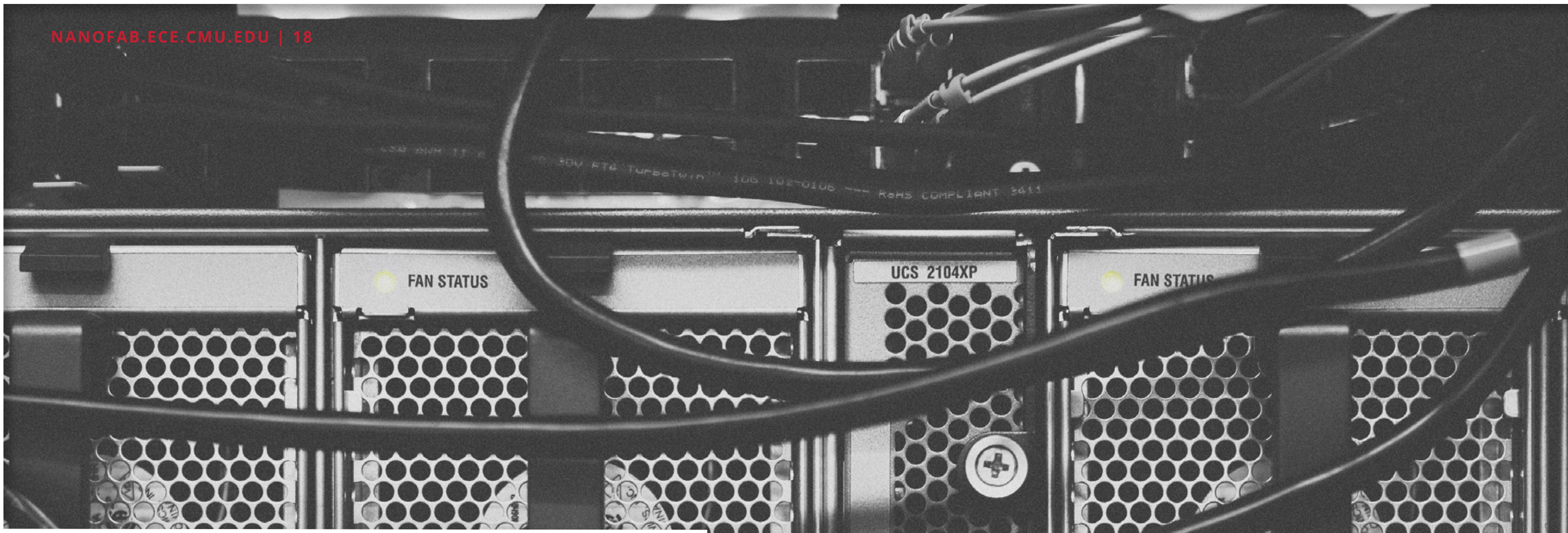
If you are interested in joining the Claire and John Bertucci Nanotechnology Laboratory, please visit our website at http://nanofab.ece.cmu.edu/.


STOP
MANUFACTURING, INC.
JST
MAGNEHELIC

2018 HIGHLIGHTS

TRANSFORMATIVE IMPACT

The Eden Hall Foundation Nanofabrication Cleanroom is having a transformative impact on the College of Engineering and the broader Carnegie Mellon community by facilitating a unique and robust nano-maker ecosystem. The acquisition and support of cutting-edge equipment, as well as an enhanced user interface and experience, positions us at the forefront of nanofabrication. These elements attract new faculty and top graduate students and enable us to support new research avenues at the micro- and nanoscale. A few examples include the following.



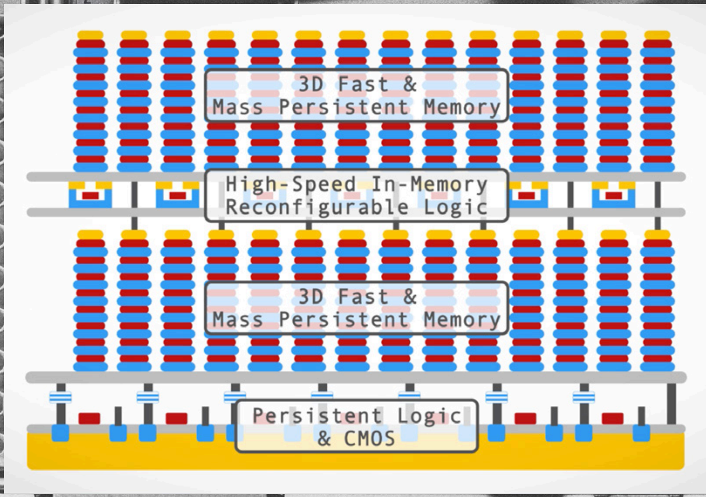
Remanence computing selected as 2018 moonshot

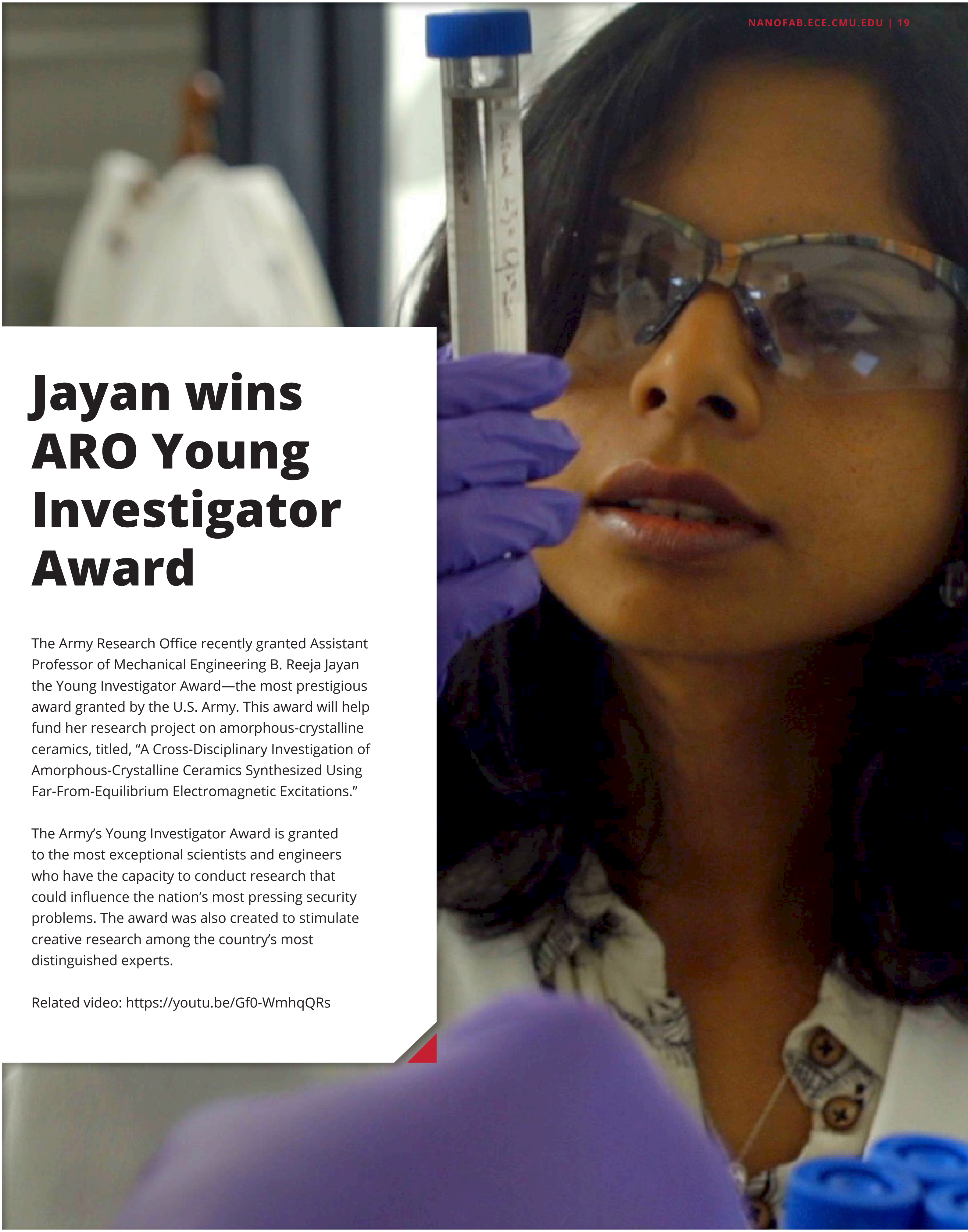
A team of faculty, lead by Electrical and Computer Engineering Professor Jimmy Zhu, has been selected as this year's moonshot, with research focused on remanence computing.

The moonshot program provides funding and support for very high-end goals for which it is difficult to obtain early-stage funding. The support from the moonshot program enables researchers to develop those ideas to a point where the team can apply for federal funding.

Remanence computing aims to fuse logic, memory, and data together on a single chip. Integrating non-volatile memory directly with the logic circuits enables data-centric computing at significantly higher speeds and lower power.

Related video: https://youtu.be/RcfWlgKraRg





Jayan wins ARO Young Investigator Award

The Army Research Office recently granted Assistant Professor of Mechanical Engineering B. Reeja Jayan the Young Investigator Award—the most prestigious award granted by the U.S. Army. This award will help fund her research project on amorphous-crystalline ceramics, titled, “A Cross-Disciplinary Investigation of Amorphous-Crystalline Ceramics Synthesized Using Far-From-Equilibrium Electromagnetic Excitations.”

The Army’s Young Investigator Award is granted to the most exceptional scientists and engineers who have the capacity to conduct research that could influence the nation’s most pressing security problems. The award was also created to stimulate creative research among the country’s most distinguished experts.

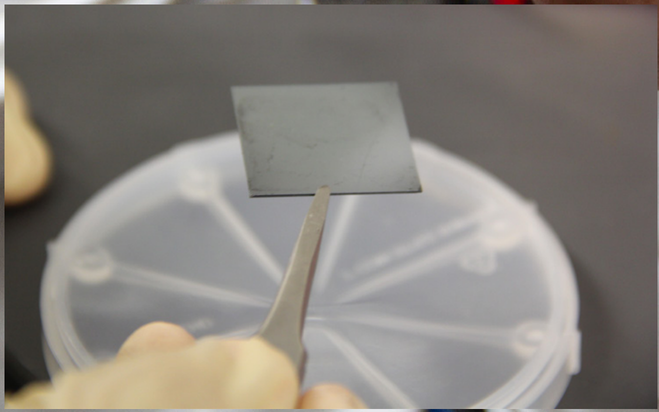
Related video: https://youtu.be/Gf0-WmhqQRs

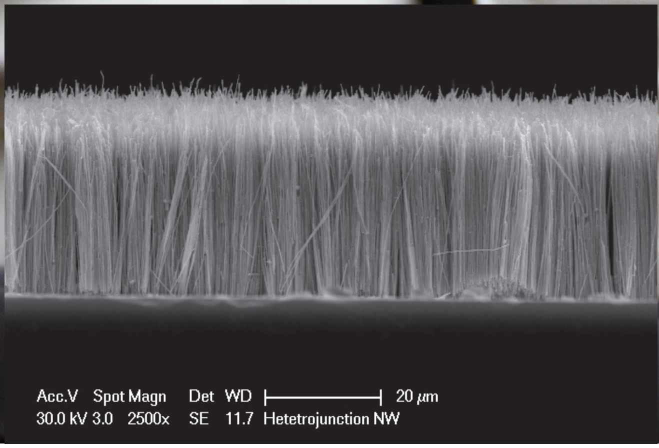
Shen, Shrestha, and de Boer published in *Nature Communications*

Mechanical Engineering Professor Sheng Shen and collaborators Ramesh Shrestha and Maarten de Boer have created a game-changing technology that can transform polymers from soft and thermally insulating materials to an ultra-strong and thermally conductive material. A paper on their work was published in *Nature Communications*.

Shen and his team have developed a polymer nanofiber that is strong, lightweight, thermally conductive, electrically insulating, and bio-compatible. They accomplished all of this in a single polymer fiber strand measuring less than 100 nanometers.
The potential impact of this development is tremendous. The characteristics of this polymer nanofiber will give it applications in aerospace and automotive systems, civil and structural engineering, medical devices, and robotics.

Related video: https://youtu.be/pn2tMoMTXxQ





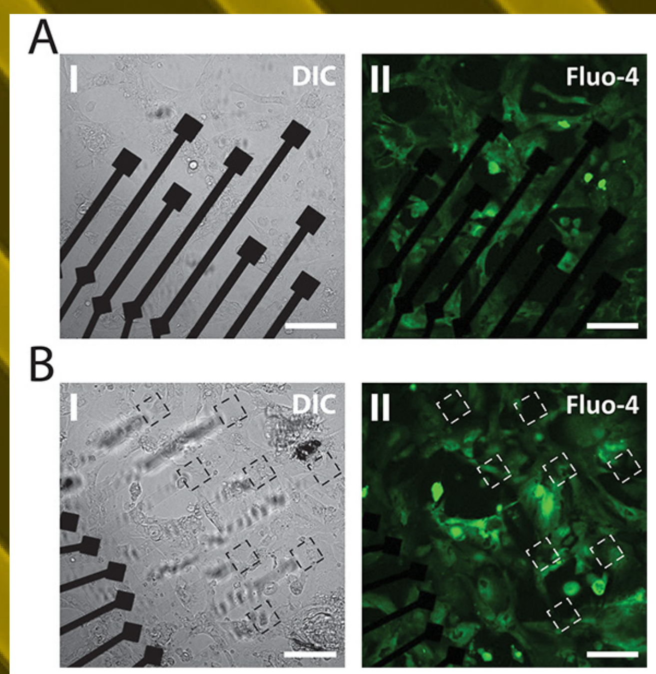
Cohen-Karni wins CMBE Young Innovator Award

Tzahi Cohen-Karni, an assistant professor of biomedical engineering and materials science and engineering, has been named a 2018 Young Innovator by the Biomedical Engineering Society's journal *Cellular and Molecular Bioengineering*. As part of the award, Cohen-Karni and his team published a research paper in the *Cellular and Molecular Bioengineering* journal. The research was supported by the Office of Naval Research Young Investigator Program.

The paper describes Cohen-Karni's work creating electrical microelectrode sensors out of graphene. By creating a unique, transparent, and biocompatible graphene-based electrical platform, the researchers have shown that they can take both optical and electrical recordings of spontaneously beating cardiomyocytes with high spatial and temporal resolution.

By enabling the investigation of both intracellular and intercellular communication processes, the researchers' transparent graphene platform will set the groundwork for investigating such diseases as Alzheimer's, Parkinson's, and heart arrhythmias.

Related video: https://youtu.be/zAp7sBj-dZI



Bettinger and collaborators published in *Advanced Functional Materials*

Associate Professor of Materials Science and Engineering and Biomedical Engineering Christopher Bettinger and his group have developed new material and processes to fabricate neural probes that mimic the mechanical properties of the nervous system.

Until now, it has been extremely challenging to develop a material and fabrication method that is flexible enough to meld with the brain but adhesive enough to stay in one place. Bettinger and his group have created a hydrogel material and fabrication process for electrodes that stick to the brain, matching its soft, flexible makeup and enabling brain-machine interfaces that don't cause damage to the brain or spinal cord.

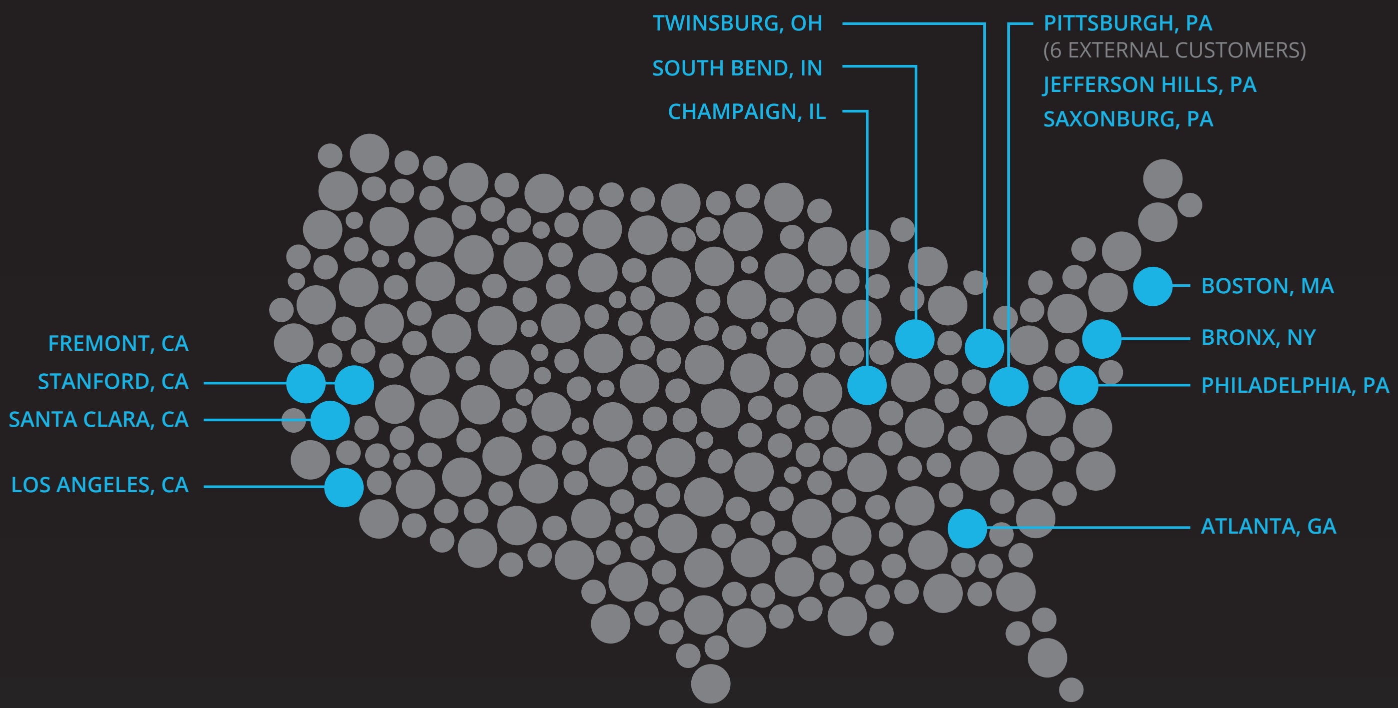
The fact that the nodes do not injure the tissue and do not move around means that they are able to record a stronger and more accurate signal from the firing neurons. The probes could now be used not only to record signals, but also to stimulate therapies.

Related video: https://youtu.be/slWVvUJeKb8

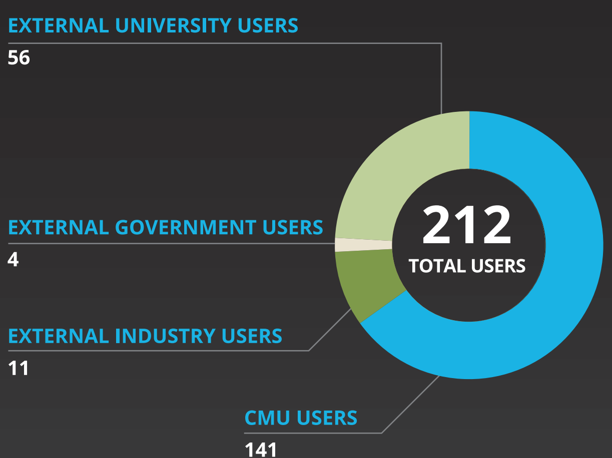

UTILITY NITROGEN
STOP
AIR PRODUCTS
EXIT
GASGUARD

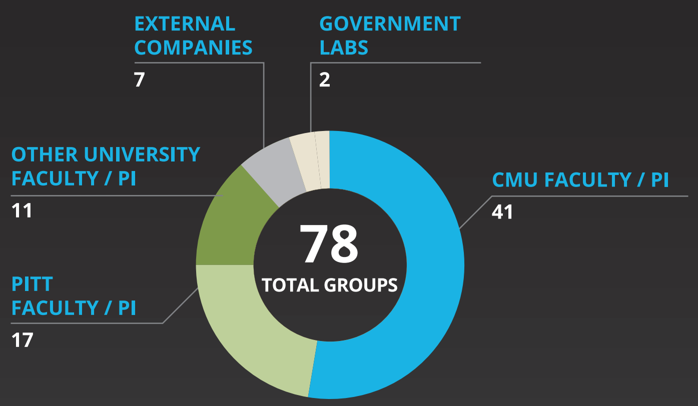
Nanofab by the numbers

NATION-WIDE USERS

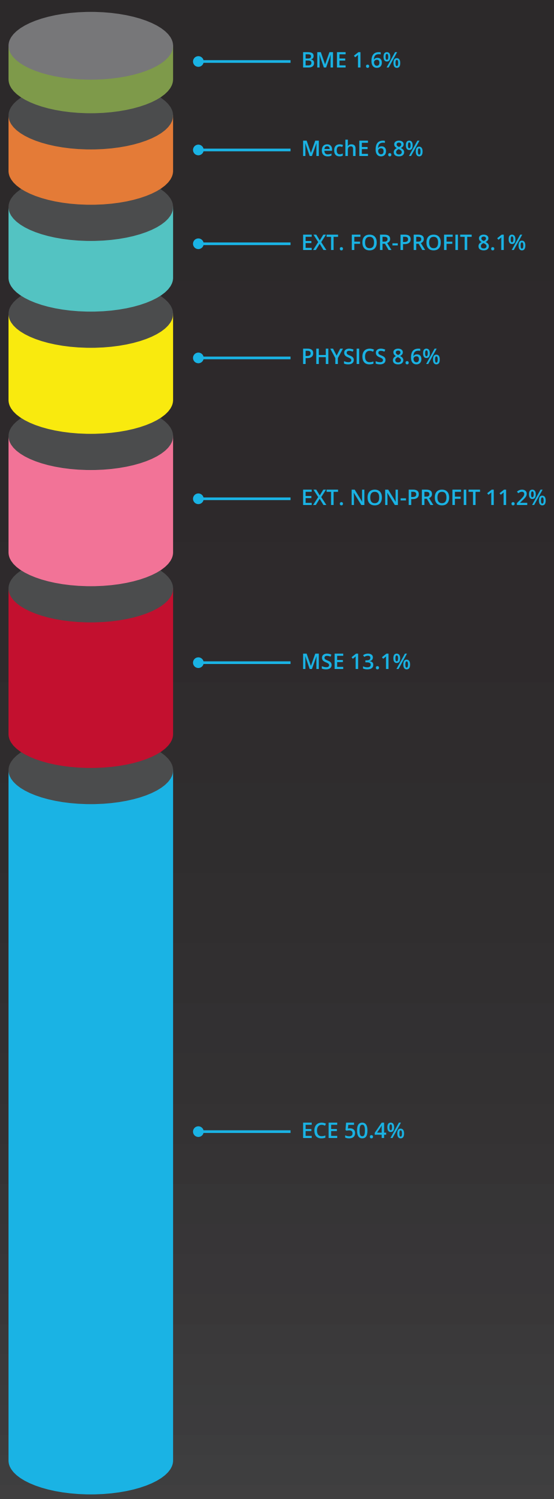


USAGE BREAKDOWNS

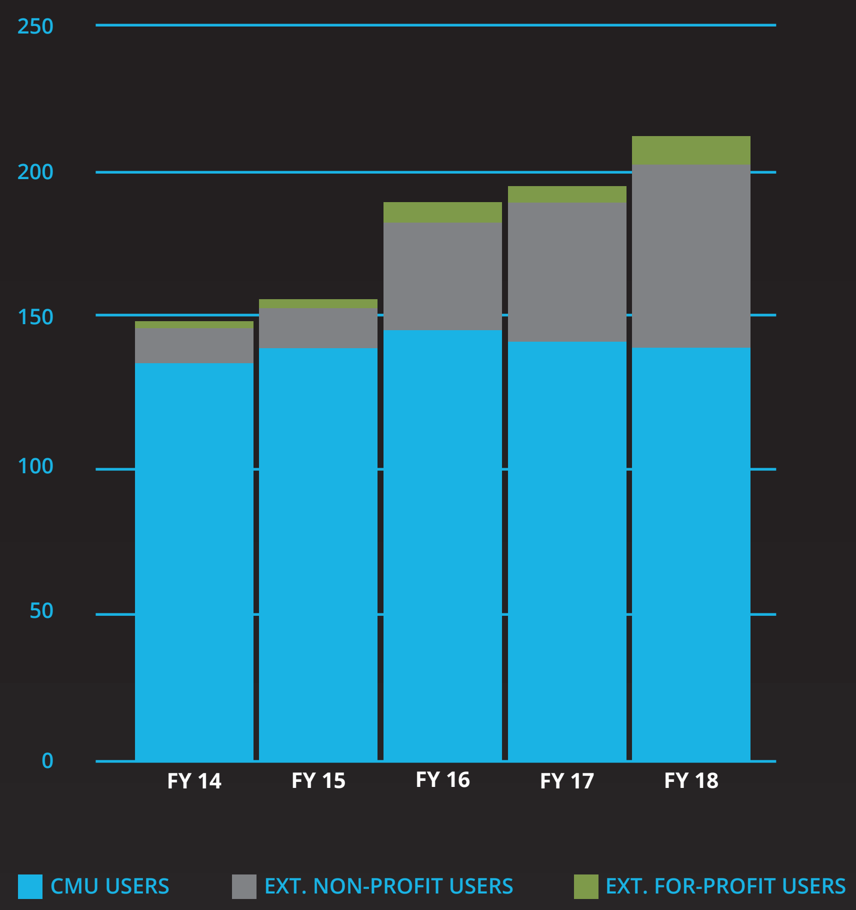




FY 17 USAGE BREAKDOWN



CUSTOMERS BY YEAR



THE NANOFAB HAS RECOGNIZED A GROWING DEMAND FROM CORPORATE, GOVERNMENT, AND ACADEMIC RESEARCHERS, AS EVIDENCED BY A 5X GROWTH IN CUSTOMERS OVER THE PAST THREE YEARS.

	FY14	FY15	FY16	FY17	FY18
CMU USERS	136	142	147	143	**141**
EXTERNAL UNIVERSITY / GOVERNMENT USERS	12	13	37	47	**60**
EXTERNAL INDUSTRY USERS	2	2	6	6	**11**
TOTAL USERS	**150**	**157**	**190**	**196**	**212**
CMU FACULTY / PI	47	51	43	43	41
PITT FACULTY / PI	5	7	14	17	17
OTHER UNIVERSITY FACULTY / PI	1	0	2	7	11
GOVERNMENT LABS	1	0	0	1	2
EXTERNAL COMPANIES	2	2	5	5	7

Nanofab facility upgrades

- 19 new wet decks
  - 3 for general or standard solvent processes
  - 4 for specialty solvent processes
  - 3 for spin-coating of resist
  - 4 for development of resist
  - 5 for acid/base processes
- 3 EMI shielded e-beam rooms
- advanced gas distribution and monitoring
- lab management software for auto logging and tool access
- increased gowning space

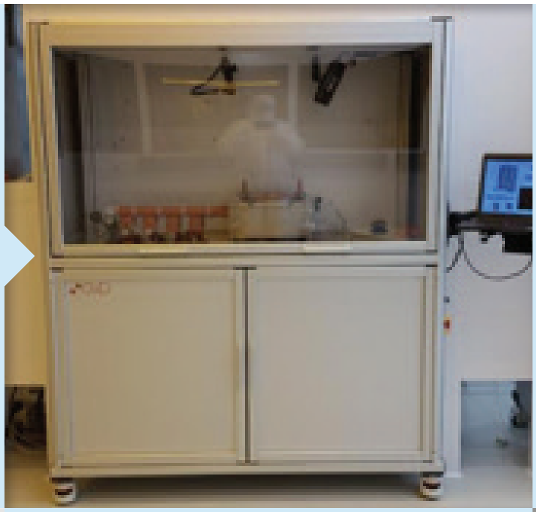
New equipment

Elionix ELS-G100 ebeam lithography system

- 100kV electron beam for high resolution up to 5nm
- 100 MHz clock for fast writing
- high alignment accuracy (20nm or better) over large wafer area
- beam currents up to 100nA for high throughput on wafers up to 6”

iLab CVD system, GVD Corporation

- initiated CVD process for the conformal growth of polymers including, but not limited to:
  - Divinylbenzene
  - PFDA
  - Methacrylates
  - Acrylates
- two heated monomer MFCs and one initiator MFC
- laser monitoring of film growth
- substrate cooling



PVD75 sputtering system, Kurt Lesker

- designed for metal deposition and includes:
  - load-lock with auto transfer
  - 6″ wafer capability
  - 6 confocal sputtering targets
  - RF, DC, and bias sputtering modes
  - confocal sputtering for up to 4 materials
  - rotary substrate holder with 800° C heater assembly
  - RF sputter etch on substrate
  - computer automation

oLab CVD, GVD Corporation

- oxidative CVD process for the conformal growth of conductive polymers, such as PEDOT
- features:
  - heated monomer MFC
  - two thermal effusion sources for material evaporation
  - rotating substrate table with heating for good film uniformity

PVD75 ebeam evaporator, Kurt Lesker

- designed for metal depositions and includes:
  - load-lock with auto transfer
  - 6″ wafer capability
  - 8 pockets (8cc each)
  - dual crystal monitors
  - water cooled rotary substrate
  - 16″-24″ variable throw height
  - RF sputter etch on substrate
  - computer automation

UV-1 ozone cleaner, Samco

- Uses UV and ozone to remove organics, including photoresist from samples up to 6″ diameter
- 300C substrate heater included for photoresist stripping and bulk removal of organic polymers
- Can also be used for UV curing and surface modification

ASML 5500/80 i-line wafer stepper

- Capable of 500nm resolution and <70nm alignment accuracy
- Set up for 4″ wafers but convertible to 3″ or 6″ platforms
- 21mm x 21mm field size
- 1.3μm depth of focus

Nanofab faculty

- Jim Bain, ECE
- Sarah Bergbreiter, MechE
- Chris Bettinger, MSE
- Rick Carley, ECE
- Maysam Chamanzar, ECE
- Tzahi Cohen-Karni, MSE/BME
- Dana Cupkova, Architecture
- Maarten de Boer, MechE
- Gary Fedder, ECE
- Randy Feenstra, Physics
- Adam Feinberg, MSE/BME
- Andy Gellman, ChemE
- Jimmy Hsia, MechE
- Ben Hunt, Physics
- Reeja Jayan, MechE
- David Laughlin, MSE
- Phil LeDuc, MechE
- Qing Li, ECE
- Shawn Litster, MechE
- Barry Luokkala, Physics
- Sara Majetich, Physics
- Carmel Majidi, MechE
- Jon Malen, MechE
- Alan McGaughey, MechE
- Michael McHenry, MSE
- Tamal Mukherjee, ECE
- Irving Oppenheim, CEE
- Burak Ozdoganlar, MechE
- Rahul Panat, MechE
- Yong-Lae Park, Robotics
- Gianluca Piazza, ECE, Faculty Director
- Larry Pileggi, ECE
- Lisa Porter, MSE
- Sheng Shen, MechE
- Marek Skowronski, MSE
- Vincent Sokalski, MSE
- Rebecca Taylor, MechE
- Elias Towe, ECE
- Yu-Li Wang, BME
- Jeff Weldon, ECE
- Erik Ydstie, ChemE
- Jimmy Zhu, ECE

Nanofab staff

- Dante Boni, Technician
- Norm Gottron, Process Engineer
- Matthew Moneck, Executive Manager
- Mason Risley, Process Engineer
- James Rosvanis, Technician
- Mark Weiler, Equipment Manager

Faculty awards and recognition

- **Jim Bain:** named associate department head of Electrical and Computer Engineering
- **Tzahi Cohen-Karni:** Cellular and Molecular Bioengineering (CMBE) Young Investigator Award
- **Randy Feenstra:** Davisson-Germer Prize in Atomic or Surface Physics from the American Physical Society
- **Reeja Jayan:** NSF CAREER Award and Air Force Office Young Investigator Award
- **David Laughlin:** Andrew Carnegie Lecture, ASM International, Pittsburgh Chapter
- **Phil LeDuc:** College of Engineering Outstanding Mentoring Award
- **Lisa Porter:** named president of the American Vacuum Society (AVS)
- **Rebecca Taylor:** U.S. Air Force Office of Scientific Research Young Investigator Award

Initiatives and Events

- Hosted AVS Symposium (2/23/18)
- Participated in Energy Week programs hosted at CMU where dozens of academics and industry engineers attend programming related to green energy technologies (4/6/18)
- Hosted mid-Atlantic cleanroom managers' meeting for approximately a dozen managers and engineers running academic and government fabs throughout the mid-Atlantic region (4/27/18)
- Participated in "CMU Engineering Workshop" attended by approximately 30 high school students (6/19/18)
- Participated in Manufacturing USA Institutes meeting (6/27/18)
- Participated in the College of Engineering's "How to be an Engineer" program designed to teach high school students and families what it means to be an engineer (10/17/18)
- Offered tours of the Nanofab to local high school students, including outreach to underrepresented minorities
- Engaged in seminars and short courses with local companies
- Trained multiple interns through summer work and work study positions
- Hosted a Biomedical Engineering course from Duquesne University for students learning about micro- and nanofabrication techniques for microfluidic devices and biomedical devices

TOUR OF APPROXIMATELY 30 HIGH SCHOOL STUDENTS

Education

The following courses have a laboratory component that is supported by the John and Claire Bertucci Nanotechnology Laboratory:

18-403: Microfabrication Methods and Technology
This course is a laboratory-based introduction to the theory and practice of microfabrication. Lectures and laboratory sessions cover fundamental processing techniques such as photo-mask creation, lithographic patterning, thin film vacuum deposition processes and wet-chemical and dry-etching processes. This is primarily a hands-on laboratory course that brings students into the microfabrication facility and device testing laboratories. Students will fabricate electronic and opto-electronic devices such as the metal-oxide-semiconductor (MOS) capacitor, the Schottky diode, the MOS transistor, the solar cell, and the light-emitting diode. An understanding of the operation of these building block devices will be gained by performing measurements of their electrical and opto-electronic characteristics. Emphasis is placed on understanding the interrelationships between the materials' properties, processing, device structure, and the electrical and optical behavior of the devices. The course is intended to provide a background for a deeper appreciation of solid-state electronic devices and integrated circuits.

18-615: Micro- and Nanosystems Fabrication
This is a new course intended to introduce students to the process flow and design methodology for integrated systems fabrication. The course will present this material through two paths. Lectures will be presented on the basic unit processes of micro- and nanosystems fabrication: deposition, patterning, and etching. Lectures will draw on examples from: semiconductor device fabrication, microelectromechanical systems (MEMS) fabrication, magnetic device fabrication, and optical device fabrication. Problem sets will be given based on this lecture material to allow students to quantitatively analyze certain process steps in detail. The second path for material presentation will be through a series of labs that allow students to design, fabricate, and test an integrated device. These laboratories will be scheduled during regular meeting times, and will use research facilities within the ECE department.

The Nanofab staff has also provided support for 48-400, an architecture course in which students are tasked with designing a manufacturing facility that would include a cleanroom. The staff offered student tours, assisted with design input throughout the semester, and sat in on the final panel where projects were presented and reviewed.

Ph.D. graduates

- Abdelgawad, Ahmed (Majetich)
- Bapna, Makund (Majetich)
- Chen, Wei (Majidi)
- Diller, Stuart (Majidi)
- El-Hinnawy, Nabil (Bain)
- Galanko, Mary Beth (Fedder)
- Guney, Metin Gokhan (Fedder)
- Hajzus, Jenifer (Porter)
- Jeong, Minyoung (Malen)
- Kwon, Ik Soo (Bettinger)
- Lau, Derek (Sokalski)
- Li, Dasheng (Skowronski)
- Liang, Hongliang (Bain)
- Lu, Xiao (Laughlin)
- Mahmoud, Mohamed (Piazza)
- Oh, Changho (de Boer)
- Xu, Changting (Piazza)
- Yu, Xiaoxiao (Gellman)

Patents

Patents awarded

- Deterministic seeding of switching filament in oxide-based memristive devices
  MA Abdelmoula, M Skowronski, AA Sharma, JA Bain; US Patent 9,997,700
- Harvesting energy from interaction with papers
  ME Karagozler, I Poupyrev, GK Fedder; US Patent 9,899,939
- Ingestible, electrical device for oral delivery of a substance
  CJ Bettinger; US Patent 9,884,011
- Low-cost fiber optic sensor for large strain
  R Panat, L Li; US Patent 9,846,276
- Melanins as active components in energy storage materials
  CJ Bettinger, JF Whitacre, YJ Kim; US Patent 9,928,968
- Method for forming a suspended lithium-based membrane semiconductor structure
  S Gong, G Piazza; US Patent 9,893,264
- Methods, apparatuses, and systems for cell and tissue culture
  Y Zeng, PR LeDuc, KH Chiam; US Patent 9,976,113
- Three-dimensional passive components
  RP Panat, DH Heo; US Patent 9,969,001
- Tip-loaded microneedle arrays for transdermal insertion
  LD Falo Jr, G Erdos, OB Ozdoganlar; US Patent 9,944,019
- Water-activated, ingestible battery
  CJ Bettinger, J Whitacre; US Patent 9,985,320

Patents applied for

- Artificial skin and elastic strain sensor
  RJ Wood, YL Park, CS Majidi, B Chen, L Stirling, CJ Walsh, R Nagpal; US Patent App. 15/823,030
- Biosensor tattoos and uses therefore for biomarker monitoring
  OB Ozdoganlar, MP Bruchez, PG Campbell, JW Jarvik, L Falo, G Erdos; US Patent App. 15/568,327
- Coated vaso-occlusive device and methods for treatment of aneurysms
  CJ Bettinger, MB Horowitz; US Patent App. 10/034,966 and US Patent App. 15/599,634
- Devices comprising muscle thin films and uses thereof in high throughput assays for determining contractile function
  KK Parker, AW Feinberg, PW Alford, A Grosberg, MD; Brigham, JA Goss; US Patent App. 15/662,371
- Ingestible electrical device for stimulating tissues in a gastrointestinal tract of an organism
  CJ Bettinger; US Patent App. 15/713,525
- Integrated electronic device with flexible and stretchable substrate
  GK Fedder, C Majidi, PR LeDuc, LE Weiss, CJ Bettinger, N Naserifar; US Patent App. 15/923,442
- Magnetic recording device
  H Li, JG Zhu; US Patent App. 15/675,135
- Methods and software for calculating optimal power flow in an electrical power grid and utilizations of same
  M Jereminov, L Pileggi, A Pandey; US Patent App. 15/658,335
- Microelectronic structures with suspended lithium-based thin films
  S Gong, G Piazza; US Patent App. 15/857,323
- Muscle chips and methods of use thereof
  KK Parker, JA Goss, A Grosberg, PW Alford, AW Feinberg, A Agarwal; US Patent App. 15/693,565
- Piezoelectric nanoelectromechanical relays
  UZ Heiba, G Piazza; US Patent App. 10/014,462
- Two-dimensional mode resonators
  G Piazza, C Cassella; US Patent App. 15/560,757

Selected research publications

Jim Bain

Novel on chip rotation detection based on the acousto-optic effect in surface acoustic wave gyroscopes
M Mahmoud, A Mahmoud, L Cai, M Khan, T Mukherjee, J Bain, G Piazza
Optics Express 26 (19), 25060-25075
DOI: 10.1364/OE.26.025060

Formation of the conducting filament in TaOx resistive switching devices by thermal-gradient-induced cation accumulation
Y Ma, D Li, A Herzing, D Cullen, B Sneed, K More, N Nuhfer, J Bain, M Skowronski
ACS Applied Materials & Interfaces
DOI: 10.1021/acsami.8b03726

A split-pole-gapped nft write head design for transition curvature reduction in heat-assisted magnetic recording
CM Chow, JA Bain
IEEE Transactions on Magnetics, 1-4
DOI: 10.1109/TMAG.2018.2835311

Experimental demonstration of aln heat spreaders for the monolithic integration of inline phase-change switches
N El-Hinnawy, P Borodulin, M King, C Furrow, C Padilla, A Ezis, D Nichols, J Paramesh, J Bain, R Young
IEEE Electron Device Letters 39 (4), 610-613
DOI: 10.1109/LED.2018.2806383

Switching dynamics of TaOx-based threshold switching devices
JM Goodwill, DK Gala, JA Bain, M Skowronski
Journal of Applied Physics 123 (11), 115105
DOI: 10.1063/1.5020070

Nanoscale thermal transport aspects of heat-assisted magnetic recording devices and materials
JA Bain, JA Malen, M Jeong, T Ganapathy
MRS Bulletin 43 (2), 112-118
DOI: 10.1557/mrs.2018.6

Magnetically actuated reconfigurable pixelated antenna
J Pal, K Deshpande, L Chomas, S Santhanam, F Donzelli, D Piazza, J Bain, G Piazza
Micro Electro Mechanical Systems (MEMS), 2018 IEEE, 791-794
DOI: 10.1109/MEMSYS.2018.8346674

Acousto-optic gyroscope
A Mahmoud, M Mahmoud, L Cai, MSI Khan, J Bain, T Mukherjee, G Piazza
Micro Electro Mechanical Systems (MEMS), 2018 IEEE, 241-244
DOI: 10.1109/MEMSYS.2018.8346529

Sarah Bergbreiter

Contact-resistive sensing of touch and airflow using a rat whisker
AET Yang, MJZ Hartmann, S Bergbreiter
2018 7th IEEE International Conference on Biomedical Robotics
DOI: 10.1109/BIOROB.2018.8487886

A lightweight, compliant, contact-resistance-based airflow sensor for quadcopter ground effect sensing
SD Gollob, Y Manian, RS Pierre, AS Chen, S Bergbreiter
2018 IEEE International Conference on Robotics and Automation (ICRA), 7826-7831
DOI: 10.1109/ICRA.2018.8461229

The principles of cascading power limits in small, fast biological and engineered systems
M Ilton, M Bhamla, X Ma, S Cox, L Fitchett, Y Kim, J Koh, D Krishnamurthy, C Kuo, F Temel, A Crosby, M Prakash, G Sutton, R Wood, E Azizi, S Bergbreiter, SN Patek
Science 360 (6387), eaao1082
DOI: 10.1126/science.aao1082

Effect of finger geometries on strain response of interdigitated capacitor based soft strain sensors
HS Shin, S Bergbreiter
Applied Physics Letters 112 (4), 044101
DOI: 10.1063/1.4998440

Characterization of a piezoelectric MEMS actuator surface toward motion-enabled reconfigurable RF circuits
MC Tellers, JS Pulskamp, SS Bedair, RQ Rudy, IM Kierzewski, RG Polcawich, SE Bergbreiter
Journal of Micromechanics and Microengineering 28 (3), 035001

Chris Bettinger

Recent advances in materials and flexible electronics for peripheral nerve interfaces
CJ Bettinger
Bioelectronic Medicine 4 (1), 6
DOI: 10.1186/s42234-018-0007-6

Reversible chemo-topographic control of adhesion in polydopamine nanomembranes
PJ Chiang, G Tang, IS Kwon, S Eristoff, CJ Bettinger
Macromolecular Materials and Engineering, 1800258
DOI: 10.1002/mame.201800258

Advances in Materials and Structures for Ingestible Electromechanical Medical Devices
CJ Bettinger
Angewandte Chemie International Edition
DOI: 10.1002/anie.201806470

Advanced cell and tissue biomanufacturing
K Ye, D Kaplan, G Bao, C Bettinger, G Forgacs, C Dong, A Khademhosseini, Y Ke, K Leong, A Sambanis, W Sun, P Yin
ACS Biomaterials Science & Engineering
DOI: 10.1021/acsbiomaterials.8b00650

Texture-dependent adhesion in polydopamine nanomembranes
IS Kwon, G Tang, PJ Chiang, CJ Bettinger
ACS Applied Materials & Interfaces 10 (9), 7681-7687
DOI: 10.1021/acsami.7b15608

Ultra-compliant peripheral nerve cuff electrode with hydrogel adhesion
X Ong, W Huang, I Kwon, C Gopinath, H Wu, L Fisher, R Gaunt, C Bettinger, G Fedder
Micro Electro Mechanical Systems (MEMS), 2018 IEEE, 376-379
DOI: 10.1109/MEMSYS.2018.8346566

Polydopamine nanomembranes as adhesion layers for improved corrosion resistance in low carbon steel
Z Ding, F Fatollahi-Fard, IS Kwon, PC Pistorius, CJ Bettinger
Advanced Engineering Materials
DOI: 10.1002/adem.201800621

Ultracompliant hydrogel-based neural interfaces fabricated by aqueous-phase microtransfer printing
W Huang, X Ong, I Kwon, C Gopinath, L Fisher, H Wu, G Fedder, R Gaunt, C Bettinger
Advanced Functional Materials, 1801059
DOI: 10.1002/adfm.201801059

Multimodal underwater adhesion using self-assembled Dopa-bearing ABA triblock copolymer networks
X Tang, CJ Bettinger
Journal of Materials Chemistry B 6 (4), 545-549
DOI: 10.1039/C7TB02371E

Maysam Chamanzar

Upconverting nanoparticle micro-light bulbs designed for deep tissue optical stimulation and imaging
M Chamanzar, D Garfield, J Iafrati, E Chan, V Sohal, B Cohen, P Schuck, M Maharbiz
Biomedical Optics Express 9 (9), 4359-4371
DOI: 10.1364/BOE.9.004359

Low-loss flexible Parylene photonic waveguides for optical implants
JW Reddy, M Chamanzar
Optics Letters 43 (17), 4112-4115
DOI: 10.1364/OL.43.004112

Ultrasonic guiding and steering of light in scattering tissue
MG Scopelliti, M Chamanzar
CLEO: Applications and Technology, ATh1Q. 2
DOI: 10.1364/CLEO_AT.2018.ATh1Q.2

Parylene photonic waveguide arrays: a platform for implantable optical neural implants
J Reddy, M Chamanzar
CLEO: Applications and Technology, AM3P. 6
DOI: 10.1364/CLEO_AT.2018.AM3P.6

Tzahi Cohen-Karni

Bioelectronics with nanocarbons
SK Rastogi, A Kalmykov, N Johnson, T Cohen-Karni
Journal of Materials Chemistry B
DOI: 10.1039/c8tb01600c

Graphene Microelectrode Arrays for Electrical and Optical Measurements of Human Stem Cell derived Cardiomyocytes
SK Rastogi, J Bliley, D Shiwarski, G Raghavan, A Feinberg, T Cohen-Karni
Cellular and Molecular Bioengineering
DOI: 10.1007/s12195-018-0525-z

Maarten De Boer

Crystalline polymer nanofibers with ultra-high strength and thermal conductivity
R Shrestha, P Li, B Chatterjee, T Zheng, X Wu, Z Liu, T Luo, S Choi, K Hippalgaonkar, M de Boer, S Shen
Nature Communications 9
DOI: 10.1038/s41467-018-03978-3

Gary Fedder

Insulation of thin-film parylene-c/platinum probes in saline solution through encapsulation in multilayer ald ceramic films
M Forssell, et al.
Biomedical Microdevices
DOI: 10.1007/s10544-018-0307-3

Ultracompliant hydrogel-based neural interfaces fabricated by aqueous-phase microtransfer printing
W Huang, et al.
Advanced Functional Materials
DOI: 10.1002/adfm.201801059

The role of hierarchical design and morphology in the mechanical response of diatom-inspired structures: via simulation
A Gutiérrez, et al.
Biomaterials Science
DOI: 10.1039/c7bm00649g

Micro and nano scale nmr: technologies and systems
O Brand, GK Fedder, C Hierold, O Tabata
John Wiley & Sons

Randy Feenstra

Quantum-confined electronic states arising from the moiré pattern of MoS2-WSe2 heterobilayers
Y Pan, S Fölsch, Y Nie, D Waters, Y-C Lin, B Jariwala, K Zhang, K Cho, J Robinson, and R Feenstra
Nano Letters
DOI: 10.1021/acs.nanolett.7b05125

Realizing large-scale, electronic-grade two-dimensional semiconductors
Y-C Lin, B Jariwala, B Bersch, K Xu , Y Nie, B Wang, S Eichfeld, X.Zhang, T Choudhury, Y Pan, R Addou, C Smyth, J Li, K Zhang, M Haque, S.Fölsch, R Feenstra, R Wallace , K Cho, S Fullerton-Shirey, J Redwing, J Robinson
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