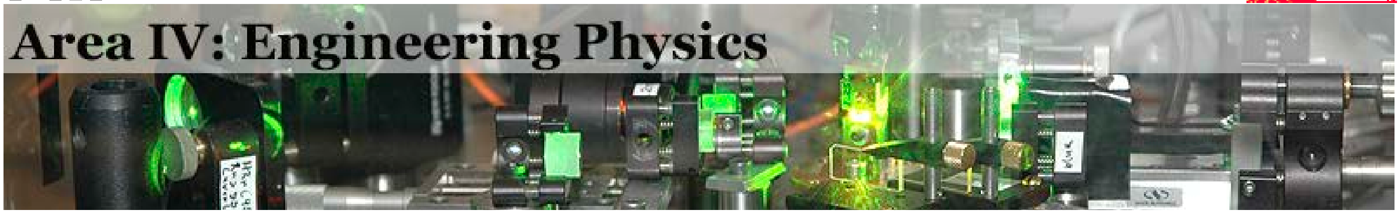
Department of Electrical Engineering and Computer Science



Guide to Graduate Study in Area IV Engineering Physics

Welcome to Area IV!

What is Area IV "Engineering Physics" about? Is Area IV about engineering or is it about physics? The simple answer is that Area IV has both, and a multitude of both in numerous multidisciplinary fields, including chemistry, materials science, mathematics, physics, electrical engineering, biology and bioelectrical engineering, and in mechanical engineering too! Area IV Engineering Physics uses the foundation and underlying principles of physics to enable the engineering of complex integrated systems. For a few examples, the systems under investigation span electronics, optoelectronics, photonics, lasers, plasma fusion, quantum communication and computation, microelectromechanical and microfluidic structures.

To help you navigate Area IV in EECS, the faculty and staff have identified nine topics that are broadly covered in the many research activities underway. The highlighted topics are electromagnetics, photonics, power, energy, materials, devices, microsystems, nanotechnology, and physics of information. For each topic, we have compiled a sampling of the research that is carried out, along with a listing of undergraduate and graduate subjects that may cover some aspect of the particular topic. In addition, many different seminars are offered each week with a particular theme that aligns well with a topic or topics. And finally, a number of central laboratories, as well as individually-supervised laboratories, are also available to conduct the multitude of Area IV research activities.

Within EECS and affiliated with Area IV, approximately 50 faculty and staff supervise research projects. The scientific and technical expertise of the faculty and staff is very broad, and their respective laboratories enable a vast array of experiments to be conducted. For your convenience, with the listing of Area IV faculty and staff, their respective alignment with an Area IV topic is also provided. You will quickly notice, however, than many topics are easily included within a single research group or research endeavor; seldom will a single research project be contained in a unique topic, but rather will span multiple research topics. The multidisciplinary nature of Area IV is very exciting and is viewed as an important enabling asset when researchers strive for an Area IV research goal or objective. In summary, Area IV contains a wealth of physics and engineering, embodied in nine topics. No boundaries exist between Area IV topics. Moreover, there also are no boundaries with the other four Areas (Area I, II, III, VII) in EECS; there is considerable overlap and many additional valuable and rewarding connections.

The amount of information regarding Area IV is overwhelming. The many, many research activities throughout Area IV are very exciting. A person, who is new to EECS at MIT, may appreciate a guide to Area IV "Engineering Physics"; I am happy to discuss Area IV and welcome your contact.

Area IV faculty chair, **Jeffrey Lang,** **lang@mit.edu**
Spring, 2012

Area IV Engineering Physics: Electromagnetics

Electromagnetics is a basic theme within Area IV and underlies most Area IV research, from power to photonics, and most Area IV graduate students either have or acquire some expertise. Beyond the Area IV research specialties discussed elsewhere, there are also faculty who study electromagnetic computational issues, magnetic fluids, meta-materials, plasmas, remote sensing, and sensors, among other topics. Both the electromagnetic subjects and the associated research focus on the complex ways in which electromagnetic fields and waves interact with all forms of matter to produce interesting and useful phenomena and devices that often motivate new mathematical approaches to the problem. Maxwell's equations and quantum mechanics are the basic tools used, although the research usually has an experimental side as well. Research Assistantships are primarily available in the Research Laboratory of Electronics, the Plasma Science and Fusion Center, and, by arrangement, at Lincoln Laboratory, located in Lexington, MA.

Area IV Engineering Physics: Photonics

Photonics is the modern science and technology of generating, manipulating, propagating and using light. Novel lasers and other sources permit the generation of light at wavelengths extending from the far infrared to the extreme ultraviolet and with characteristics that make possible a wide range of applications. Advances in materials, fabrication and device design create new opportunities for optimizing the interactions between photons and electrons and among photons themselves. Nanostructures, integration, and the quantum nature of light itself further extend the range of the capabilities of photonics.

Research in EECS at MIT comprises activities directed at advancing the full spectrum of these enabling technologies. Femtosecond lasers are developed for studies of ultrafast phenomena in materials and devices, for optical clocks and frequency combs, for arbitrary waveform generation, for photonic analog-to-digital conversion and for signal processing based on ultra-precise synchronization and timing distribution. Femtosecond lasers are also employed in nano-surgery for studying neural regeneration and degeneration, as well as for 3-D medical imaging via optical coherence tomography. High energy and high power few-cycle laser pulses are produced to study high intensity phenomena, to generate extreme ultra-violet and x-ray radiation and to extend capability into the attosecond time domain. Frequency swept lasers are developed for ultra-broadband imaging, and highly stable and frequency locked lasers are applied for fundamental measurement and quantum optics.

Device technologies being employed include fiber optics, III-V semiconductor heterostructures, organic materials, photonic crystals, and silicon nanophotonics. Research for communication applications ranges from designs of new device structures that generate, control and detect light, to studies of sub-systems and network architectures needed for future commercial advances, to methods for controlling quantum information and enabling quantum communication. The possibility of using silicon photonics to enhance communication and functionality within computers is also the focus of much exciting research.

Area IV Engineering Physics: Power

Electric power systems convert energy to electrical form, transport electric power over geographic distances, deliver the power to users and control the whole process. Electric utility systems have been in existence for over 100 years and are now a major part of our economies. Sources of electric power include falling water, fossil fuel generation from coal, petroleum and natural gas, heat from nuclear fission, and small amounts from burning biomass, from wind and solar heat and from direct conversion using solar photovoltaic cells. There are also electric power systems that are parts of vehicles (automobiles, trucks and trains, ships and airplanes).

Research in electric power systems at MIT is carried out in several departments. Research in Electrical Engineering and Computer Science involves a number of different areas of investigation, including renewable generation (chiefly solar photovoltaic systems but also generators for wind turbines), adaptation of power systems to large amounts of renewable generation through load adaptive control, monitoring and control of elements of the power system, electromechanical devices for use of electric power (motors) and high voltage insulation systems.

Area IV Engineering Physics: Energy

This summer we are updating our Area IV website and this particular page describing research in ***Energy*** is being revised. Please revisit this page soon for a detailed description of our work in Energy. [28 Aug 2009]

Area IV Engineering Physics: Energy

Research ***in Materials*** in Area IV is extremely comprehensive and naturally begins with utilizing a variety of deposition techniques including chemical vapor deposition and hydrothermal deposition, molecular beam deposition and molecular beam epitaxy, and also more typical sputtering techniques, as well as self-assembly methods. Mature material systems used to form complex and advanced device structures are studied based on Si, GaAs, GaSb, InP, SiGe, with growing interest in wide bandgap materials based on GaN. In the case of inorganic III-V compounds, complex heterostructures are designed and grown with alloy layers having mixtures of column III atoms as well as mixtures of column V atoms. Such III-V-based heterostructures also contain quantum wells, quantum dots and quantum dashes for enhanced optical and electronic properties.

Significant effort is devoted to depositing and understanding the physical properties of organic thin films, hybrid organic/inorganic structures, polymer solids and self-assembled materials. Presently active organic layers have thickness on the nanoscale, but research emphasis is to reduce the size to that of a single molecule. Novel synthesis techniques are developed to form carbon nanotubes, fullerenes and semiconductor nanowires, and recent work is devoted to forming graphene sheets of carbon that are a single atom thick. Superconducting materials and structures are investigated to exploit their quantum-mechanical properties for electronics. In all of the material-oriented research, opportunities for developing electronic, photonic and optoelectronic devices with enhanced performance is the goal. Devices include LEDs and lasers, photodetectors and transistors, solar cells, chemical sensors, isolators, memory cells, micro-electromechanical and micro-fluidic devices, as a few examples.

Area IV Engineering Physics: Devices

Building on the wealth of research in *Materials*, Area IV faculty and research staff design, create, and investigate a multitude of devices involving complex combinations of organic and inorganic semiconductors, polymers and small molecules, magnetic materials and carbon or graphene sheets. Faculty/research staff expertise in the topic areas of *Microsystems* and *Nanotechnology* are an enabling capability that is brought to bear to advance contributions in devices. The many different devices that are investigated include display devices, flexible and transparent optoelectronic devices and multi-color emitters, semiconductor lasers and optical amplifiers, THz and solid-state lasers, light emitting diodes, solar cells, photodetectors, MOSFETs and high-electron mobility transistors, and thermoelectric and thermo-photovoltaic devices. Ultracapacitors, having performance enhanced by the use of nanotubes offers research in energy storage devices.

Implementing material machining at the micro-scale and nano-scale, photonic crystal devices are created and investigated, along with nano-fluidic filters, micro-sensors and micro-actuators. In all cases, fundamental chemistry, physics, materials science, as applied to the macro-scale and nano-scale, provide the foundations to examine new phenomena, such as electrostatics at the micro-scale for bio-molecule manipulation and transport in nano-space. As one might expect, the topic of ***Devices***, in Area IV Engineering Physics, naturally weaves together many of the other highlighted topics contained in the research endeavors of Area IV. A research project in the topic of ***Devices*** will necessarily be multidisciplinary.

Area IV Engineering Physics: Microsystems

This summer we are updating our Area IV website and this particular page describing research in ***Microsystems*** is being revised. Please revisit this page soon for a detailed description of our work in Microsystems. [28 Aug 2009]

Area IV Engineering Physics: Nanotechnology

The MIT EECS Department contains a comprehensive ***nanotechnology*** program entitled nanoeecs (**http://www.eecs.mit.edu/nanoeecs/**) that includes a variety of subdisciplines ranging from nanophotonics to nanfoabrication. Of these subdisciplines, several are focused on area IV, Engineering Physics, topics, including those listed below:

Nanofabrication, ***nanomaterials***, and ***nanobiomaterials***: The fabrication of nanostructures and the synthesis of new materials are the building-blocks upon which nanotechnology is advanced and focused on a multitude of applications. The tools and techniques of nanofabrication and nanomaterials are presented in a range of EECS courses (see below).

Nanobiotechnology: Quantitative understanding, manipulation and use of biological systems at nanoscopic length scales are the major goals of nanobiotechnology research. Many technologies are developed and used to study a variety of biosystems, including nano/micro-fluidics, precision electronics, femtosecond optics, computational models and molecular probes.

Nanoelectronics, magnetics, optics, and energy: Electromagnetism applied at the nanoscale can be used to exploit a wide variety of phenomena, including ultrafast electronics and organic molecules that emit light.

To learn more about the nanoeecs program, and to get a detailed listing of the courses available, please visit **http://www.eecs.mit.edu/nanoeecs**.

Area IV Engineering Physics: Physics of Information

"Information" is an abstract concept, a measure of "surprise," which governs computation and communication, while "Physics" describes the natural world, with laws governing the behavior of atoms, electrons, and other concrete objects. Research in the topic of ***Physics of Information*** in Area IV links these two fields, and seeks to discover and understand how new kinds of information processing and communication are enabled by different laws of physics. Two examples illustrate our efforts in the Physics of Information:

Beyond Silicon – the most successful platform for modern information processing is the silicon chip, but at present rates of advancement, individual logic gates will soon reach size scales at which bits of information will need to be encoded in individual molecules or atoms, or in single electrons and photons; and time scales will soon reach beyond nanoseconds, to the need for control at the picosecond and femtosecond regime. Significant research thus focuses on alternative devices and system models for computation. This includes the development of all-optical logic gates, realized with a microfabricated integrated waveguide Mach-Zehnder interferometer, using the nonlinearity of an embedded semiconductor material to allow photons to interact with each other. Nonlinear optics also provides, in the ultrafast regime, femtosecond optical frequency combs, which allow absolute measurement to one part in 1015, useful for realizing high speed, ultra-low noise analog-to-digital converters. And at sub-nanometer length scales, carbon nanotubes allow capture and control of single molecules for novel post-silicon electronic devices.

Quantum Information – ultimately, size and time scales are reached at which the physical laws switch from the classical behavior of Newton and Maxwell to the quantum behavior governed by Schrödinger and von Neumann. Surprisingly, quantum systems can solve certain mathematical and computational problems exponentially faster than is known possible with just classical systems, as has been demonstrated in experiments at MIT. Research here in Area IV spans a broad range of physical systems, using microfabricated chips to trap and control single atoms, and microscopic superconducting Josephson junctions to realize quantum bits. These devices have coherence times up to one second, and build on results by Area IV faculty demonstrating simple quantum algorithms such as quantum factoring, with nuclear spins in molecules. Research in Area IV also shows how measurement with quantum states can improve imaging resolution beyond the diffraction limit, and how quantum states can allow communication at rates exceeding the Shannon limit.

Physics of Information in Area IV also plays a strong role in a major program at MIT- interdisciplinary Quantum Information Science and Engineering (iQuISE), an NSF-funded Integrative Graduate Education, Research, and Training (IGERT) program supporting graduate students, and the development of a comprehensive curriculum in quantum information science and engineering at MIT.

The following research programs also contribute to ***physics of information***:

- **Center for Extreme Quantum Information Theory** see: **http://xqit.mit.edu/**
- **Quantum Information Science @ MIT** see: **http://qis.mit.edu/**
- **Interdisciplinary Quantum Information Science and Engineering** see: **http://www.rle.mit.edu/iquise/**

Area IV Engineering Physics: Seminars

The following seminars are organized within Area IV and provide an opportunity to learn the latest results in research.

- **Optics and Quantum Electronics Seminar** see: **http://www.rle.mit.edu/oqe/seminar/** Wednesdays, 11am, room 36-428 (Haus Room)
- **Quantum Information Science@MIT** see: **http://qis.mit.edu/seminars.php**
- **Center for Ultracold Atoms Seminar** see: **http://cuaweb.mit.edu/Pages/Seminars.aspx**
- **Center for Integrated Photonic Systems (CIPS) Brown Bag Seminar Series** see: **http://www.rle.mit.edu/cips/**
- **NanoStructures Lab (NSL) Group Meeting** see: **http://nanoweb.mit.edu** Fridays, 3pm, room 36-428
- **Microsystems Technology Laboratories VLSI Seminar** see: **http://www-mtl.mit.edu/news/seminars/index.html** Tuesdays, 4pm, room 34-101
- **Small Talks** see: **http://pergatory.mit.edu/smalltalks/** Wednesdays, 4pm, room 36-462 (Allen Room)
- **Micro/Nano-Technology Seminar Series** see: **http://www.rle.mit.edu/mnss/** Thursdays, 3pm, RLE Conference Center, room 36-462/428
- **LEES seminar** Thursdays, 4pm, 32-145

Area IV Engineering Physics: Laboratories and Facilities

The research in Area IV Engineering Physics is carried out in a number of locations around MIT and includes central facilities that are open to the entire campus, as well as individually-supervised laboratories. Research facilities within an individual research group are typically available, on an arranged basis, to all students of MIT. In the central facilities, students are trained in the proper use of equipment and safe practice when in the lab. Additionally, a number of technician-operated facilities are available for students to access. Below is a brief description of a number of laboratories and facilities supervised by Area IV faculty and research staff.

- Core facilities of **Center for Biomedical Engineering** (A.J. Grodzinsky, Director): a description of the microscope imaging facility is found at **http://web.mit.edu/cbe/www/facilities.html**.

- Central facilities of **Institute for Soldier Nanotechnologies** (**ISN**) (J.D. Joannopoulos, Director): the central facilities of the ISN, located at bldg. NE47 500 Technology Square, contain a multitude of equipment needed for nano-processing complete with characterization and extensive modeling as well. The following link offers an insight into the equipment that is available in the ISN central facility: **http://web.mit.edu/isn/newsandevents/isnnews/isnnews903.pdf**

- Within the **Plasma Science and Fusion Center** (**PSFC**), the largest university laboratory of its kind in the US, a key facility is the Alcator C-Mod Tokamak. The Alcator Tokamak produces plasma conditions approximating those required for fusion and operates at the highest magnetic field of any magnetically-confined fusion experiment in the world. The facilities are available to all departments at MIT and to a number of plasma research groups. Additionally, within the Plasma Electrodynamics Group, significant computational facilities are available and are located in room 38-268. [See the website: **http://rleweb.mit.edu/rlestaff/p-bers.htm**]. For those who are interested, brochures are available from the PSFC, located in NW16 and NW17 and outside room 38-266.

- Within the **Research Laboratory of Electronics**, **the Nanoprecision Deposition Laboratory** is a state-of-the-art facility established for the layer-by-layer deposition of materials, especially compound semiconductors and dielectrics. Two deposition techniques are available including molecular beam epitaxy, for III-V compound semiconductors containing arsenic, phosphorus and antimony, and ion beam deposition for dielectrics of silicon dioxide or tantalum pentoxide. In the photo, left, the molecular beam epitaxy system has two ultrahigh vacuum reactors that are interconnected to a central cluster tool for wafer loading and processing. The molecular beam epitaxy system is capable of handling more than one wafer and is also capable of depositing material onto wafers having up to 8 inch diameters. See **http://web.mit.edu/cbegroup/www/laboratory.html**.

- Facilities in the **Nanostructures Laboratory** (**NSL**) support the development of advanced processing tools and techniques for fabricating surface structures with feature sizes down to a few nanometers. Facilities are available for photo-, interferometric, and nano-imprint lithography. In addition, the NSL houses materials and processing facilities for etching (chemical, plasma, and reactive-ion), lift-off, electroplating, sputter deposition, and electron-beam evaporation. See **http://nanoweb.mit.edu/**.

- **Scanning-Electron-Beam Lithography Facility** (**SEBL**): The scanning-electron-beam lithography facility enables writing of arbitrary pattern geometries over large area substrates (up to 150 mm). Features as small as 5 nm on pitches as narrow as 10 nm have been fabricated. The facility includes two SEBL systems, a VS26 and a Raith 150. The former was developed at IBM Research Center specifically for electron-beam lithography and operates at 50keV. The Raith 150 is a Zeiss scanning electron microscope modified for electron-beam lithography by the addition of a laser interferometrically-controlled stage, blanking electronics and software. For more information see: **http://www.rle.mit.edu/sebl/**.

- The **Optics and Quantum Electronics Group** of the Research Laboratory of Electronics has world leading facilities for ultrafast optics and integrated photonics, including femtosecond lasers with a variety of capabilities, advanced instrumentation for ultrafast and ultra-broadband measurement, optical fiber devices and optical probes for nanoscale diagnostics. These facilities are used for research on optical clocks and frequency standards, optical networks, and densely integrated photonic circuits, as well as studies of ultrafast phenomena in materials and devices and the development of new femtosecond capabilities. More information about the people and activities of this group can be found at **http://www.rle.mit.edu/oqe/people.htm**.
- MIT is engaged in a comprehensive program of research into various aspects of microelectronics that encompasses fabrication, design and architecture. The research in Area IV relevant to microelectronics includes work on: semiconductor materials and materials processing, the development of novel devices and device structures, microelectromechanical and microfluidic devices, structures, and systems. The physical resources to support microsystems and nanotechnology research are located in Bldg. 38 and 39; the **Microsystems Technology Laboratories** (**MTL**) complex also provides for computer-aided design (CAD), testing and masking facilities. A brief description of the various laboratories is below; however, more extensive detail is found on the MTL Web page: **http://mtlweb.mit.edu/services/index.html**.
- The **Integrated Circuits Research Laboratories** (**ICL**) is a complete state-of-the-art integrated circuits and fabrication laboratory containing 2800 sq. ft. of class 10 space, and equipped with a full complement of facilities for the fabrication of microelectronic circuits with features at or below the 1µm level. The ICL, as well as the Technology Research Laboratory (see below), is staffed and operated by professional personnel, and qualified students can make arrangements for direct access.
- The **Technology Research Laboratory** (**TRL**) provides nearly 4000 sq. ft. of space, with 2200 sq. ft. being class 100, where graduate students and staff carry out novel process development. A wide variety of common-use and research-group specific equipment is housed in the TRL.
- Of course, research in Area IV includes fundamental studies of materials and devices and necessarily therefore requires characterization capability; such capability is found in the **Center for Materials Science and Engineering** (**CMSE**) with a link at **http://web.mit.edu/cmse/facilities/mit.html**. The **Shared Experimental Facilities** (**SEFs**) found in CMSE offer researchers state-of-the-art electron microscopy, x-ray diffraction, crystal growth and extensive material analysis including surface, thermal, and optical material analysis. These facilities are available to any member of the MIT community and are maintained by a team of qualified research personnel. Following the proper training for the use of various pieces of equipment, qualified graduate students are welcome to use the equipment individually.

Area IV Undergraduate Preparation and Graduate Program

Undergraduate Preparation

Students in Area IV Engineering Physics should have an exposure to some, or all of, the following subjects:

i) Electromagnetics such as obtained in an undergraduate physics program or electrical engineering program. At MIT an example course is 6.013 “Electromagnetics and Applications” or an equivalent course that studies quasistatic and dynamic solutions to Maxwell’s equations. A basic understanding of radiation, diffraction, waves, coupling to structures, guided and unguided waves, resonance, forces, power and energy would be very valuable for students entering Area IV.
ii) Solid-state electronics and physics at an undergraduate level would be helpful and might be similar to the experience gained in 6.012 “Electronic Devices and Circuits” or the more advanced subject 6.720 “Integrated Microelectronic Devices”. Device and circuit modeling concepts found in these two aforementioned MIT classes may be found in typical subjects that address transistor physics or physical electronics at other schools.
iii) Modern physics at an undergraduate level that includes quantum and statistical thermodynamics would be very valuable; an example MIT class is 6.728 “Applied Quantum and Statistical Physics.”
iv) Mathematics is very important and entering Area IV students should have a good background in complex variables, analysis, probability, and linear algebra. The respective MIT subjects in mathematics include: 18.04, 18.100, 6.041 (or 18.313) and 18.06.

If an entering Area IV student is lacking major elements of the above background, the faculty strongly encourage one to take the appropriate undergraduate subject or subjects as part of the student’s overall plan for graduate school.

Graduate Program in Area IV

The graduate program in Electrical Engineering contains no required subjects. Each program is tailored to fit the needs and professional objectives for every student; the student’s graduate counselor, research advisors, and Area chair are great resources for consultation. As you peruse the pages describing the highlighted topics in Area IV, you will see key subjects listed that contain elements of that particular topic. In addition to subjects that are taught routinely in the Fall and Spring semesters, a number of special subjects are also taught either Fall or Spring and sometimes in alternating years. Once a student has selected a research group, or has clearly identified a particular area of research that he/she will pursue, the list of subjects includes more specialized and advanced graduate subjects. Check the EECS section of the **MIT Open Course Ware** (OCW) or for EECS classes on the **MIT Catalogue section for Course 6**. You will find descriptions of all EECS subjects, undergraduate and graduate, along with the semester in which they are offered.

The guidelines for the **Master of Engineering** and the **Master of Science** programs include the completion of four graduate level H subjects and a Master's research thesis. The Master's degree is expected to be completed within two years. All students are expected to complete a Master's degree prior to admission into the doctoral program in EECS.

The **EECS doctoral program** has two qualification examinations: the **Technical Qualifying Evaluation** (see the Department **TQE grid, pdf**) and the **Research Qualifying Examination** (RQE). In electrical engineering, each student must demonstrate competence in four distinct areas; competence is established by satisfactory scholarship in four introductory graduate level subjects. Competence is established by earning an A grade in three of the four subjects selected from the list of approved subjects for the TQE. To successfully pass the TQE, a minimum of three A grades and one B grade is allowed. Your graduate counselor will provide guidance for selection of appropriate subjects to successfully complete the TQE. Students unable to demonstrate competence in all four selected areas will be required to complete an oral exam to prove competency. After the Master's degree is obtained, the RQE exam can be completed by preparing a short written report of your research that is submitted to your RQE committee; accompanying the written report is an oral presentation to demonstrate your research understanding and competency.

In addition to the qualification exams, students must complete a minor (two classes), successfully complete the assignment of teaching assistant for one semester, and complete two additional subjects as suggested by their PhD research thesis committee.

EECS research--including several major projects involving Area IV Engineering Physics faculty and graduate students--was spotlighted on the EECS homepage. See the complete research spotlight: **http://www.eecs.mit.edu/spotlights/gradstudents_researchST09.html**.

To read more about the EPIC project pictured above, see: **http://www.eecs.mit.edu/spotlights/grads-research09_6.html** and "High speed analog-to-digital conversion with silicon photonics" Proc. SPIE**, Vol. 7220, 72200B (2009)**; DOI:10.1117/12.808952 and the website that further describes this and other research in the **Optics and Quantum Electronics Group**, Research Laboratory of Electronics, **RLE**.