Solid-State Engineering, 1999–2000

Externally Funded Research Projects

Electrical and Thermal Characterization for New Ternary Rare-Earth Based Materials for High Performance Thermoelectrics
C. R. Kannewurf*
Sponsor: Defense Advanced Research Projects Agency / Michigan State University

The goal of this program is to discover new rare-earth and main-group-element materials having a high thermoelectric figure of merit. The focus is on narrow bandgap, heavy-element semiconductors and new ternary and quaternary compounds having itinerant electrons occupying a narrow distribution of energy near the Fermi level. These materials possess structural and electronic-band features that make them excellent candidates for use as thermoelectrics.

Electroactive Molecular & Polymeric Materials Thrust Group
C. R. Kannewurf*
Sponsor: National Science Foundation

This is an ongoing investigation of polymer-based mixed conductors and nanocomposite materials such as the intercalation of polymers into semiconducting vanadium oxides. Attention is now also being given to possible organic device structures and conducting ceramics.

Electronic and Thermal Characterization of Solid Chalcogenides Using Molten Salts
C. R. Kannewurf*
Sponsor: National Science Foundation / Michigan State University

A number of new compounds have been prepared of the type ALn_3Te_8 (A=Cs or Rb, Ln=Ce; A=K, Ln=Nd) which display an interesting defect square. For such materials, recent theory predicted a charge-density wave that leads to infinite zig-zag $(Te^{2-}_2)n$ chains and Te^{2-}_3 anions. The present work constitutes the first experimental confirmation of this prediction. Initial transport measurements on both single crystals and pressed pellets indicate p-type conduction for narrow-gap semiconductors.

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*Denotes Solid State Engineering Group faculty member(s), listed in alphabetical order.

MOCVD Research Project

C. R. Kannewurf*

Sponsor: National Science Foundation / Science and Technology Center for Superconductivity

A considerable effort has been spent on the determination of the key superconducting parameters for the thin-film project where the MOCVD preparation technique has been successfully employed for the major high-T_c systems. In collaboration with Argonne National Laboratory, recent work has involved the development of an ion-beam-assisted deposition system for preparing oxide buffer layers for the creation of coated conductors. The initial results for critical current density measurements are quite encouraging.

Novel Bismuth Chalcogenides as Thermoelectric Materials

C. R. Kannewurf*

Sponsor: Office of Naval Research / Michigan State University

The initial work on this program has led to the development of new thermoelectric materials. Notable results were obtained for the Cs-Bi-Te and K-Bi-Se systems. In particular, $CsBi_4Te_6$ has been identified as the best thermoelectric material below 300˚K, surpassing the figure of merit for all Bi_2Te_3 compositions in that range. At present, compositions from the K-Bi-Se system are being exploited by industry to develop devices operating above 300˚K.

Equipment for In-Situ Monitoring of RHEED

N. Newman*

Sponsor: Ballistic Missile Defense Office

This project provides instrumentation for in-situ characterization of material properties during III-N growth. Novel synthesis methods are being developed for the development of (1) optoelectronic devices in the blue to deep-UV spectral range and (2) high-temperature and high-power electronic devices.

Investigation of Microwave Loss in Ferroelectrics and Dielectrics

N. Newman*

Sponsor: Defense Advanced Research Projects Agency

This project involves a systematic investigation of the properties of ferroelectrics for microwave resonator and filter applications. This work studies the characteristics of the host material and existing lattice defects which cause microwave loss. The methods used will directly identify the physical source of loss, allowing for a systematic improvements in the performance of high-Q tunable microwave resonators and filters.

Investigation of Thermodynamic and Kinetic Factors Involved in Synthesis of III-N Thin Films

N. Newman*

Sponsor: Office of Naval Research

This project explores the synthesis of III-N semiconductors and their alloys using a novel metastable growth process. The goal is to develop a fundamental understanding of the issues involved in producing novel, ultra-high-efficiency III-N devices operating in the blue-to-ultraviolet spectral region. Extensive modeling and characterization of the electronic properties of the material is performed in conjunction with thin-film growth. Specific efforts are aimed at the optimization of AlN and its alloys for optoelectronic applications in the ultraviolet spectral region.

Advanced Lasers and Detector Integrated Systems (ALADINS)

M. Razeghi*

Sponsor: Defense Advanced Research Projects Agency / Office of Naval Research

The objective of this four-year project is to develop advanced lasers and photodetectors operating in the ultraviolet (UV)-blue wavelength range between 365 and 450 nm. To date, only Nichia Chemicals in Japan has successfully demonstrated and commercialized (as of October 1, 1999) a long lifetime continuous wave violet laser diode emitting at 400 nm, while no other institution is even close to this stage. The focus of this project will be to demonstrate low threshold continuous wave, edge emitting lasers in this country which can compete with or be better than the current state of the art. When integrated, such laser and photodetector components would be capable of performing two distinct tasks that benefit the needs of future DoD missions for sensing and recognition.

AlGaN for Solar-Blind Focal Plane Arrays

M. Razeghi*

Sponsor: Defense Advanced Research Projects Agency / Office of Naval Research

Wide bandgap AlGaN semiconductors are novel materials which hold the promise to revolutionize numerous optoelectronic and electronic systems by making these less costly, more efficient, and more reliable. The objective of this project is to deposit atomic layers of $Al_xGa_{1-x}N$ films by metalorganic chemical vapor deposition, design and fabricate ultraviolet (UV) photodetectors utilizing these materials. The key desired property is both their high sensitivity to UV light and, at the same time, their insensitivity to visible and infrared light. To date, the Center has been the first to demonstrate solar blind detectors and has achieved the highest efficiency and wavelength versatility for such UV photodetectors.

Demonstration of Uncooled InAsSb Photodetectors for Military Sensors

M. Razeghi*

Sponsor: Defense Advanced Research Projects Agency / Office of Naval Research

InAsSb alloys have the lowest bandgaps among technically available III-V compound materials. These materials can be used for long-wavelength infrared detection ($\lambda > 10$ μm). Device structures for room-temperature or near-room-temperature operation are developed and fabricated using the MOCVD technique. This project is one of the first experimental demonstrations of these materials for long-wavelength photodetection applications in an uncooled environment.

Electron Beam Lithography

M. Razeghi*

Sponsor: Office of Naval Research

Enhancing the performance and functionality of optoelectronic and electronic systems requires smaller dimension components. However, the current limitations of optical lithography lie on the order of 0.5 – 1 μm. Further reducing the size of devices would necessitate the use of electron beam lithography. The objective of this grant is to acquire and demonstrate an electron beam lithography system which can achieve 30 nm scale features.

Fabrication and Characterization of AlGaN UV Solar-Blind Photodetectors

M. Razeghi*

Sponsor: Office of Naval Research

Detection of small ultraviolet signals without interference by ambient sunlight is very important in defense applications such as flame detection and missile countermeasures. AlGaN alloys are ideal for solar-blind photodetectors since they have high rejection ratios against ambient visible light. This project demonstrates solar-blind AlGaN ultraviolet detectors having rejection ratios of 10^6, the highest ever reported.

Fellowship: Development of AlGaN UV Photodetectors

M. Razeghi*

Sponsor: National Aeronautics and Space Administration Goddard Space Flight Center

This fellowship supports a graduate student studying the development of AlGaN ultraviolet photodetectors. The research includes optimized etching and metal-contact techniques on these hard-to-fabricate materials. High-speed metal-semiconductor-metal photodetectors are demonstrated with maximum operating frequencies up to 92 GHz.

GaIn(As)P–GaAs Very-Long-Wavelength Quantum-Well Infrared Photodetectors

M. Razeghi*

Sponsor: Air Force Office of Scientific Research

Infrared imaging in the very-long-wavelength range is essential in many space and defense applications. This project demonstrates very-long-wavelength InGaAlAs / InP QWIP's operating in the 13–19 μm infrared range with very sharp spectral width $\Delta\lambda/\lambda$ of only 10%.

Growth and Fabrication of Multi-Quantum Well Infrared Photodetectors

M. Razeghi*

Sponsor: Air Force Office of Scientific Research

Multi-spectral infrared focal-plane arrays (FPA's) are needed for applications such as advanced infrared targeting and tracking, nonmetallic land-mine detection, and noninvasive medical diagnosis. This project demonstrates the first two-color, voltage-tunable, InGaAs / InAlAs and InGaAs / InP QWIP's at 4 μm and 8 μm on low-cost InP substrates.

Infrared Semiconductor 3–5 μm High Power InAsSb Based Injection Laser

M. Razeghi*

Sponsor: Air Force Research Laboratory

The objective of this work is to develop high-power, high-temperature semiconductor injection mid-infrared lasers through the design, growth and characterization of Sb-based Strained-Layer Superlattice (SLS) laser structures emitting with $\lambda \sim 4$ μm operating in pulse and continuous mode. The prior related research on both Sb-based double heterostructure (DH) and multiple quantum well (MQW) lasers shows that the use of Sb-based growth technology for mid-infrared laser diodes has been properly developed, and a well established processing technique has been optimized for this material system. Additionally, the initial research on SLS lasers has produced lasers with record operating characteristics which demonstrates the feasibility of these lasers to operate with high output powers at high temperatures.

Investigation of III-Nitride Alloys for UV Photodetectors and Blue-Green Lasers

M. Razeghi*

Sponsor: Office of Naval Research

The physical processes of how lasing takes place in InGaN material systems are not fully understood. This project studies the physical origin of the radiative-recombination process in GaN, AlN, and AlGaN III-N nitrides alloys in both theory and experiment. Model calculations are performed for optical gain and luminescence emission in TE and TM polarization with strain and quantum-size effects. Based on this newly-developed physical understanding, high-speed, high-resistivity GaN p-i-n photodiodes and AlGaN photoconductors are demonstrated up to a maximum operating frequency of 98 GHz and a wide range of detection wavelengths as short as $\lambda = 200$ nm, a record.

Large Area Lateral Epitaxial Overgrowth of GaN on Silicon Substrates

M. Razeghi*

Sponsor: Office of Naval Research

Combining the strengths of wide bandgap GaN semiconductors and of the silicon technology can bring revolutionary technical breakthroughs in numerous optoelectronic and electronic systems, as well as considerably decrease their packaging cost and increase their reliability. Lateral epitaxial overgrowth is a novel technique that allows growth of GaN on very dissimilar substrates. This project aims at developing and improving this technique on silicon substrates to achieve large area low defective GaN wafers. By following this approach, we have demonstrated the first high quality GaN films on silicon substrates with a dramatically reduced defect density.

QWIP on Silicon Effort – Phase II

M. Razeghi*

Sponsor: Nova Research, Inc. / U.S. Air Force Rome Lab

This project is a research and development effort with the goal of growing a high quality InGaAs/InP QWIP detector structure onto a silicon structure. We characterize the resulting detector structure by measuring I-V curves, signal and dark current response, spectral responsivity, and D*. An additional goal is to deposit an array of detectors onto the backside of a wafer containing readout circuitry on the top side.

Semiconductor Laser for 2–5 μm and 7–9 μm Region / Quantum Cascade Lasers

M. Razeghi*

Sponsor: Defense Advanced Research Projects Agency / U.S. Army

The quantum cascade laser is a novel type of semiconductor laser that is based on electronic radiative transition between subbands within a quantum well, and can be used for long wavelength laser emission (λ = 3 to 20 μm). In order to realize this type of laser, it is necessary to make atomic scale thin layers of semiconductors with an angstrom resolution. Our work aims at developing a device design model and experimentally realize the device using state-of-the-art semiconductor technology. In this project, room temperature operation of quantum cascade lasers with maximum optical output power up to 0.77 W was demonstrated by researchers at the Center for the first time using single-step growth method based on gas-source molecular beam epitaxy technique.

Travel Funds — 10th ISPSA-2000, Seoul, Korea

M. Razeghi*

Sponsor: Office of Naval Research

The project sponsored the organization and administration of the *International Symposium on Physics of Semiconductors* held during Nov. 2000 at Cheju Island, Korea .

Uncooled Photon Detectors for IR Imaging

M. Razeghi*

Sponsor: Office of Naval Research

Infrared photon detectors that can operate at room temperature (i.e., uncooled) hold great promise for numerous situations by making such components more cost efficient, smaller, and more reliable. They would also be several orders of magnitude faster than currently existing technology which relies on thermal detectors. This project aims at developing novel semiconductor materials and growth technology, as well as device structures and designs to realize this cutting-edge device. To date, researchers at the Center have been demonstrated photon detectors with similar sensitivity to thermal detectors, but nearly six orders of magnitude higher speed.

Patents Issued

M. G. Kanatzidis, D.-Y. Chung, C. R. Kannewurf*, T. Hogan, and L. Iordanides, “Alkali Metal Chalcogenides of Bismuth Alone or With Antimony,” U.S. Patent no. 6,013,204, Jan. 11, 2000.

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Book

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Book Sections and Chapters

M. Razeghi*, “21st Century: The Final Frontier for III-Nitrides Materials and Devices,” pp. 381–395 in *Future Trends in Microelectronics: The Road Ahead*, S. Luryi, J. Xu, and A. Zaslavsky, eds. New York: Wiley, 1999.

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Journal Papers

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A. Matlis, S. Slivken, A. Tahraoui, K. J. Luo, J. Diaz, Z. Wu, A. Rybaltowski, C. Jelen*, and M. Razeghi*, “Low-threshold and high power λ~9.0 μm quantum cascade lasers operating at room temperature,” *Applied Physics Lett.*, vol. 77, no. 12, 18 Sept. 2000, pp. 1741–1743.

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M. Razeghi,* P. Kung, P. Sandvik, K. Mi, X. Zhang, V. P. Dravid, J. Freitas, and A. Saxler, "LEO of III-nitride on Al_2O_3 and Si substrates," *SPIE Conf. Proc. – Photodetectors: Materials and Devices V*, vol. 3948, 2000, pp. 320–328.

M. Razeghi,* P. Sandvik, P. Kung, D. Walker, K. Mi, X. Zhang, V. Kumar, J. Diaz, and F. Shahedipour, “Lateral epitaxial overgrowth of GaN on sapphire and silicon substrates for ultraviolet photodetector applications,” *Materials Science and Engineering B: Solid-State Materials for Advanced Technology,* vol. B74 (1-3), May 1, 2000, pp. 107–112.

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M. Wraback, H. Shen, P. Kung, M. Razeghi*, J. C. Carrano, T. Li, and J. C. Campbell, “Ultraviolet detector materials and devices studied by femtosecond nonlinear optical techniques,” *SPIE Conf. Proc. – Photodetectors: Materials and Devices V*, vol. 3948, 2000, pp. 352–362.

Symposium Sessions Organized / Chaired

C. Jelen*, Member Tech. Committee, “Infrared Detectors and Materials IV,” *SPIE Photonics West*, Jan. 2000.

N. Newman*, Co-Organizer, “Substrate Engineering,” *Materials Research Soc.*, Boston, MA, Nov. 29 – Dec. 3, 1999.

N. Newman*, Co-Organizer, *Lawrence Symp. on Critical Issues in Epitaxy*, Mesa, AZ, 2000–2001.

M. Razeghi*, Member Adv. Committee, *Low Dimensional Structures and Devices* (LDSD’99), Alanya, Turkey, Sept. 15–17, 1999.

M. Razeghi*, Chair, “Photonics and Optoelectronics Sessions,” *Int. Semiconductor Device Research Symp.* (ISDRS ‘99), Charlottesville, VA, Dec. 1–3, 1999.

M. Razeghi*, Panel Member, “Enabling Technologies for the New Millennium,” *Int. Semiconductor Device Research Symp.* (ISDRS ‘99), Charlottesville, VA, Dec. 1–3, 1999.

M. Razeghi*, Member Adv. Committee, *10th Int. Workshop on Physics of Semiconductor Devices* (IWPSD '99), New Delhi, India, Dec. 14–18, 1999.

M. Razeghi*, Chair, "Photodetectors Materials and Devices V," *SPIE Int. Symp. on Optoelectronics 2000*, San Jose, CA, Jan. 26–28, 2000.

M. Razeghi*, Chair, "Infrared Detectors and Materials I," *SPIE Int. Symp. on Optoelectronics 2000*, San Jose, CA, Jan. 26–28, 2000.

M. Razeghi*, Member Program Committee, *10th Int. Conf. on Metalorganic Vapor Phase Epitaxy* (ICMOVPE-X), Sapporo, Japan, June 5–9, 2000.

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Invited Talks and Seminars

C. R. Kannewurf*, "Thermoelectrics: The Second Time Around," *Argonne National Laboratory, Energy Technology Division*, Argonne, IL, Oct. 1999.

A. Wang, N. L. Edelman, J. R. Babock, T. J. Marks, M. Yan, R. P. H. Chang, M. A. Lane, P. W. Brazis, C. R. Kannewurf*, P. A. Lee, and N. R. Armstrong, "Growth Process - Doping - Microstructure-Charge Transport Relationships in Transparent Conducting Oxide Thin Films," *42nd TMS Electronic Materials Conf.*, Denver, CO, June 2000.

N. Newman*, "Ferroelectric/Dielectric Filters for RF Systems," *ONR Topical Workshop on High Performance Tunable Filters for the Advanced Multifunction RF System* (AMRFS), Rosslyn, VA, 1999.

N. Newman*, "MBE Synthesis of Ill-V Semiconductors: A Model System of Meta-Stable Growth," *Lawrence Symp. on Critical Issues in Epitaxy*, Mesa, AZ, 1999.

M. Razeghi*, "Lateral Epitaxial Overgrowth of GaN on Sapphire and Silicon Substrates for Ultraviolet Photodetector Applications," *Low Dimensional Structures and Devices* (LDSD'99), Alanya, Turkey, Sept. 15–17, 1999.

M. Razeghi*, "High Power Mid-Infrared III-V Semiconductor Injection Laser Diodes," *Low Dimensional Structures and Devices* (LDSD'99), Alanya, Turkey, Sept. 15–17, 1999.

M. Razeghi*, "GaInAsP-GaAs VLW QWIPs," *Air Force Office of Scientific Research Program Review Meeting*, Dayton, OH, Sept. 28–30, 1999.

M. Razeghi*, "Roadmap of Semiconductor Laser Diodes for WDM: Recent Advances and Future Trends," *Wavelength Division Multiplexing—Systems and Applications* (WDM–SA '99), National Institute of Standards and Technology, Gaithersburg, MD, Nov. 3–4, 1999.

M. Razeghi*, "High Power 3–12 μm Laser Diodes: Recent Advances and Future Trends," *LEOS Annual Meeting*, San Francisco, CA, Nov. 8–11, 1999.

M. Razeghi*, "Advanced Electronic and Optoelectronic Devices from Engineered Type-II Sb-Based Superlattices," *Int. Semiconductor Device Research Symp.* (ISDRS '99), Charlottesville, VA, Dec. 1–3, 1999.

M. Razeghi*, "High Quality, Low Noise III-N Photodiodes," *Int. Semiconductor Device Research Symp.* (ISDRS '99), Charlottesville, VA, Dec. 1–3, 1999.

M. Razeghi*, "First Demonstration of High-Speed Uncooled Type-II Superlattices for Long Wavelength Infrared Detection," *Int. Semiconductor Device Research Symp.* (ISDRS '99), Charlottesville, VA, Dec. 1–3, 1999.

M. Razeghi*, "Lateral Epitaxial Overgrowth of GaN: Materials and Devices," *Int. Semiconductor Device Research Symp.* (ISDRS '99), Charlottesville, VA, Dec. 1–3, 1999.

M. Razeghi*, "Future Trends of III-Nitrides Using Lateral Epitaxial Overgrowth," *10th Int. Workshop on Physics of Semiconductor Devices* (IWPSD '99), New Delhi, India, Dec. 14–18, 1999.

M. Razeghi*, "Inaugural / Keynote Address," *10th Int. Workshop on Physics of Semiconductor Devices* (IWPSD '99), New Delhi, India, Dec. 14–18, 1999.

M. Razeghi*, "New Approaches in Uncooled Infrared Photodetectors: Sb-Based III-V Compound Semiconductors," *10th Int. Workshop on Physics of Semiconductor Devices* (IWPSD '99), New Delhi, India, Dec. 14–18, 1999.

M. Razeghi*, "LEO of III-Nitride on Al_2O_3 and Si Substrates," *SPIE Int. Symp.on Optoelectronics 2000*, San Jose, CA, Jan. 26–28, 2000.

M. Razeghi*, "Ultraviolet Detector Materials and Devices Studied by Femtosecond Nonlinear Optical Techniques," *SPIE Int. Symp.on Optoelectronics 2000*, San Jose, CA, Jan. 26–28, 2000.

M. Razeghi*, "Growth and Characterization of Very Long-Wavelength Type-II Infrared Detectors," *SPIE Int. Symp.on Optoelectronics 2000*, San Jose, CA, Jan. 26–28, 2000.

M. Razeghi*, "Growth and Characterization of Type-II Non-Equilibrium Photovoltaic Detectors for Long-Wavelength Infrared Range," *SPIE Int. Symp.on Optoelectronics 2000*, San Jose, CA, Jan. 26–28, 2000.

M. Razeghi*, "High-Responsivity GaInAs/InP Quantum Well Infrared Photodetectors Grown by Low-Pressure Metalorganic Chemical Vapor Deposition," *SPIE Int. Symp.on Optoelectronics 2000*, San Jose, CA, Jan. 26–28, 2000.

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