COLORADO HIGHER EDUCATION COMPETITIVE RESEARCH AUTHORITY
University of Colorado:Colorado State University:University of Northern Colorado:Colorado Schools of Mines:State of Colorado

March 10, 2011

Honorable Members of the House and Senate Education Committees
State Capitol
200 East Colfax
Denver, CO 80203

Re: Annual Report of the Colorado Higher Education Competitive Research Authority

Dear Senators and Representatives:

Colorado Revised Statute §23-19.7-103(3) requires the Colorado Higher Education Competitive Research Authority (the "Authority") to report annually to the Education Committees of the Colorado House of Representatives and Senate on research projects funded by the Authority in the previous calendar year. This letter reports on calendar year 2010.

The National Science Foundation awarded two Materials Research Science and Engineering Center grants in 2008 to Colorado, one to the Colorado School of Mines and one to the University of Colorado. The CHECRA has pledged $400,000 per year to each of these projects. The Authority made payments of $400,000 each to the two MRSECS in 2010.

The Colorado School of Mines grant, $9.3 million over six years, is focused on investigating emerging renewable energy materials, such as the next generation of solar panels and fuel cells. It is the first NSF-funded center dedicated solely to renewable energy technologies. The second award is a continuation of CU's Liquid Crystal Research Center. This Center's research is contributing to a number of different fields, including better liquid crystals for solar panels and the origins of DNA.

The Authority also made the first of four pledged payments of $400,000 to Colorado State University for its Extreme Ultraviolet Engineering Research Center.

Attachments A-C have more detailed information on each of the three projects that received funding in 2010.

During calendar year 2010, the Authority received quarterly distributions from the waste tire recycling fees totaling $373,415. The Authority also received a single distribution of Limited Gaming Funds of $1,904,250. Interest earnings on those funds and the prior year's receipts totaled

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$14,109, for a total income of $2,291,775 in 2010. As described above, the Authority distributed $1,200,000 in matching grants. The Authority fund balance on December 31, 2010 was $1,565,865.

Please contact me if you have any questions.

Sincerely yours,

Rico Munn
Chair

1560 Broadway, Suite 1600, Denver, Colorado 80202 • (303) 866-2723 • fax (303) 866-4266

ATTACHMENT A

Engineering Research Center in Extreme Ultraviolet Science and Technology
Colorado State University
University of Colorado
Director: Prof. Jorge J. Rocca. Colorado State University
Deputy Director: Prof. Margaret M. Murnane. University of Colorado
CHECRA Grant: $200,000 (2008, 2009), $400,000 (2010-2013)

Project Summary

The National Science Foundation (NSF)-funded Extreme Ultraviolet Science and Technology Engineering Research Center, a partnership between Colorado State University and the University of Colorado, is a world leader in the generation and application of light beyond the ultraviolet to challenging scientific and industrial problems that include nanotechnology, advanced materials, clean energy, and in the near future biology. The Center, supported by a $4 million per year base grant from the NSF, is making important contributions to the research output, education, and economical health of the state. The funding provided by the Colorado Higher Education Competitive Research Authority (CHECRA) was crucial in assisting the Center to achieve renewal by the National Science Foundation in 2010, which extends funding by NSF until October 2013. It also significantly contributed to the Center's ability to demonstrate excellent technical progress, and secured more than $8 million in Federal funding to Colorado during 2010.

Description of the project, the principal persons or entities involved in the project

Light in the Extreme Ultraviolet (EUV) region of the spectrum (wavelengths approximately 1 to 50 nm) has become a critical enabling technology in areas of great importance to the national economy, as the size of the most advanced electronic circuits and nanoscale machines continues to shrink below the wavelength of visible light. Furthermore, exciting new opportunities in science arise from the possibility of focusing EUV light to unprecedented small spot sizes, short pulse durations, and extremely high intensities. Further development of EUV technologies will open up a variety of new areas of investigation, including new tabletop probes of surface, chemical, cellular samples, nanostructures and materials, and the development of a new generation of nanoprobes. In response to these challenges and opportunities, in October 2003 NSF funded the ERC in Extreme Ultraviolet Science and Technology.

The Center combines the complementary expertise of Colorado State University and the University of Colorado—leaders in compact EUV light sources and applications—with a set of partner institutions that include the University of California Berkeley/Lawrence Berkeley National Laboratory and four year Colleges, other universities, national laboratories, and a set of sixteen industrial corporate members. At Colorado State University Center the faculty includes Profs. Jorge Rocca, Carmen Menoni, Mario Marconi, and Elliot Bernstein with affiliations to the Electrical Engineering, Chemistry and Physics departments. At the University of Colorado the Center Faculty includes Profs. Margaret Murnane, Henry Kapteyn and Ronguii Yang, with affiliations to the Physics Department, JILA, the Electrical and Computer Engineering and Mechanical Engineering Departments.

To realize the full impact of EUV technology in manufacturing and in scientific research we are developing a new generation of compact coherent EUV sources with unique capabilities and we are combining them with advanced EUV optics to implement engineered systems designed to solve challenging engineering and scientific problems. Breakthroughs in new EUV lasers and in High Harmonic Generation sources have significantly expanded their spectral coverage, in some cases increasing the average power by orders of magnitude. In the past year we have made significant advances in the development of compact high brightness coherent EUV and soft x-ray sources and have broken new ground and established new records in integrating them into engineered systems. By integrating the new compact sources with advanced EUV optics, we have developed a new set of microscopes, materials modification stations, and spectrometers with unique capabilities for a broad range of applications in industry and science. These include compact EUV microscopes with sub-38 nm resolution, a laser ablation testbed capable of producing sub-100 nm holes, an EUV photoacoustic metrology testbed to characterize thin films, a lensless microscope with 20 nm spatial resolution and elemental sensitivity, a single photon ionization spectrometer for the study of nanoclusters, a table-top workstation for the patterning of arrays of nanostructures;

This Center makes an important contribution to education in Colorado, ranging from graduate education to elementary school. We are addressing the shortage of engineers and scientist with expertise in EUV technology by training a large number of students and young scientists, several of which have now graduated and joined industries in Colorado. Our Research Experience for Undergraduate program has already mentored more than 150 students, with a significant fraction of the summer participants from under-represented minority groups. We have also developed a successful set of workshops for K-12 students and teachers. The Center supports High School student researcher internships during the summers, and also has a program in which Middle School teachers spend part of the summer conducting research at the Center and developing material they can take back to the classroom. Optics teaching kits containing materials and curriculum for standards-based hands-on activities were distributed to over 100 K-12 teachers. In 2010 we again held the annual "Optics After School" Lab program for High School Students. This 5 day event has enrolled the participation of 153 High School students since the Center started. To further ensure the active participation of under-represented groups, the Center is working with the Colorado Louis Stokes Alliance for Minority Participation at CSU, the Science Discovery Program at CU–Boulder.

The amount of funding allocated to each principal person or entity, manner in which each entity applied the funding in connection with the project, and results achieved

The $400K in state matching funds to the Center for 2010 were used to support graduate students and young scientists who worked in collaboration at Colorado State University and at the University of Colorado to develop new sources of EUV laser light. These new light sources are enabling the development of a new generation of more powerful microscopes and other tools for studying materials and devices of nano-scale dimensions.

At Colorado State University, $200K of the CHECRA matching funds were used to support two young research scientists. They worked in close collaboration with graduate students and the PI in the development of new EUV laser light sources, and in ultra-high resolution microscopy and in the nanopattering of materials. During the 2010 year the research succeeded in extending the useful output of these lasers to shorter wavelengths and in demonstrating a new technology that will make these lasers more compact for applications, consisting in the use of efficient diode lasers as the energy source to power them. In 2010 the Center demonstrated the first EUV lasers fully pumped by diode lasers. Other recent advances include the use of these unique lasers as sources of illumination in new ultrahigh resolution microscopes. During 2010 one of these EUV laser-based microscopes was used to assess the quality of EUV lithography masks for the fabrication of the next generation of computer chips. In another development performed in collaboration with industry (Avago, Fort Collins) a new compact EUV microscope was used for the first time to acquire "flash images" of a rapidly ocillating Micro-Mechanical-Machine-System (MEMS) system with nanometer spatial resolution. A new spin off company, XUV Lasers [**www.xuvlasers.com**], was started in Fort Collins to commercialize the technology developed at Colorado State University.

The University of Colorado used their $200K State Matching funds for the NSF EUV ERC to provide partial support to two graduate students and two postdoctoral researchers. These students and postdocs worked on key technologies of the Center – the development of advanced, next-generation, laser and x-ray sources, and also the development of new microscopy techniques. Progress has been excellent in developing very high average power lasers, and in developing experimental and theoretical schemes to convert laser-light into x-rays. A major advance occurred in 2010, with the demonstration of laser-like beams up to photon energies of 1keV, which are of interest for whole cell imaging and magnetic materials imaging at the nanoscale with elemental and chemical sensitivity. Many applications of these technologies are being implemented in collaboration with NIST Boulder Labs, industry and other collaborators including: the development of new microscopes capable of high-resolution nanoimaging of thick materials and biological samples; characterization of interfaces and thin films of interest to the semiconductor and data storage industries; measurements of heat transport in nanostructures of interest to electronics and photovoltaics; and understanding and optimizing magnetic materials on nanoscale dimensions for applications in data storage. [see references] Past work on laser and x-ray sources has already been commercialized and has led to a 25-person spin-off company in Boulder. [KMLabs link:**www.kmlabs.com.**] The current work on new coherent x-ray sources and advanced microscopes will also be commercialized in the future.

Summary to Benefits to the State of Colorado

- In 2010 the Center was renewed by NSF until October 2013, amounting in $ 8,400,000 in NSF core funding for the period (Oct 2010-Oct 2013)
- Generated more than $ 8 M in funding from Federal Agencies during 2010 for Colorado State University and University of Colorado;
- Attracted $ 263,000 in funding from industry in 2010.
- Supported ~ 50 graduate and undergraduate students and faculty in Colorado;
- Graduated numerous students with PhD or MS degrees who were hired by Colorado high technology companies (e.g. Brooks Automation, KM Laboratories, InPhase, Avago);

- Assisted Colorado companies in bringing new products to the market (e.g., Precision Photonics, KM laboratories);
- Provided research experiences for more than 10 undergraduate students;
- Reached 1500 K-12 students and teachers with science workshops and demonstrations during 2010. This included 47 teachers.
- Continued to provided summer research experiences for middle school teachers and high school students (five high school students and four Colorado teachers during 2010).
- Increases the National and International reputation of Colorado as a leader in advanced
- technology and science;
- A spin off company, XUV Lasers, was started in Fort Collins to commercialize the technology developed at Colorado State University.

Center Journal Publications for 2010

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4. S. Heinbuch, F. Dong, J.J. Rocca, and E.R. Bernstein, "Experimental and theoretical studies of reactions of neutral vanadium and tantalum oxide clusters with NO and NH_3," J. Chem. Phys. **133**, 174314 (2010).
5. F. Brizuela, S. Carbajo, A. Sakdinawat, D. Alessi, D.H. Martz, Y. Wang, B. Luther, K.A. Goldberg, I. Mochi, D.T. Attwood, B. La Fontaine, J.J. Rocca, and C.S. Menoni, "Extreme ultraviolet laser-based table-top aerial image metrology of lithographic masks," Optics Express **18**, 14467 (2010).
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9. P. Ranitovic, Xiao-Min Tong, B. Gramkow, S. De, B. DePaola, K. P. Singh, W. Cao, M. Magrakvelidze, D. Ray, I. Bocharova, H. Mashiko, A. Sandhu, E. Gagnon, M. Murnane, H. Kapteyn, I. Litvinyuk and C.L. Cocke, "IR-Assisted Ionization of Helium by Attosecond XUV Radiation," New Journal of Physics 12, 013008 (2010).
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Renewable Energy Materials Research Science and Engineering Center
Colorado School of Mines
CHECRA Grant: $400,000 (per year for 6 years)

Summary: The Materials Research Science and Engineering Center (MRSEC) at the School of Mines, under the leadership of Dr. Craig Taylor, is focused on investigating emerging renewable energy materials, such as enhancing solar panels through nanotechnology and improving membrane technologies important to renewable energy applications, such as batteries, fuel cells and electrolyzers.

Description of the project, the principal persons or entities involved in the project, and the amount of funding allocated to each principal person or entity

With annual global energy consumption expected to increase to as much as 30 terawatts by 2050 and mounting concerns over oil reserve depletion, energy security, and global warming, meeting world energy demand will be one of the grand challenges of the 21st century. While renewable and alternative technologies have the potential to address the most serious concerns with fossil fuels, cost is a major obstacle to their widespread deployment. There has been remarkable progress, for example, in lowering the price of photovoltaic (PV) electricity generation, yet present costs are nearly ten times higher than electricity produced from coal. Similar price differentials exist when comparing fuel cells with conventional electricity generators. Estimates based on historical trends give several decades before many renewable technologies become competitive. Transformative technological innovation is the key to accelerating this time line and fundamental advances in materials science will spearhead this process.

The MRSEC consists of two Interdisciplinary Research Groups (IRGs). IRG1 is concentrating on materials of potential use in the next generation of PV devices, but the scope of this IRG will be much broader since the systems of interest have important properties in common with a wide range of other electronic and opto-electronic materials. The important questions this IRG is attempting to answer involve the scattering and relaxation mechanisms that govern electronic transport in semiconducting materials of use in PV applications, especially mechanisms that are altered in nanostructured environments. These nanostructures include quantum wires and quantum dots, which have potential for significant improvements in efficiency by tuning the optical and electronic properties through size, composition, and surface termination, and by uniquely quantum mechanical effects, which offer possibilities for collecting solar radiation that is lost in conventional cells. The long-term research directions of this IRG are aimed at producing transformative changes in PV technology through significant improvements in materials properties that result from development of fundamental concepts for more efficient carrier generation and collection.

The second Group (IRG2) is concentrating on advanced membranes for renewable energy applications, with the scope being also much broader since the systems to be studied include polymers, ionic solids, and hybrid systems. Solid electrolyte materials and membrane technologies are central to many processes in the conversion, utilization, and storage of energy.

Very frequently, ionic transport is the "weak link" in electrochemical energy storage or conversion systems. At present, the myriad interactions that occur in ion transport membranes—ion-ion, ion-solvent, and ion-electrode—are poorly understood. Fundamental research is crucially needed to provide the knowledge required for the intelligent design of novel transport membranes with highly optimized properties. IRG2 is fabricating novel transformative ion conducting materials by synergistically combining materials with dramatically different ionic transport characteristics. An additional part of IRG2 involves the evaluation of clathrate structures as potential materials for hydrogen storage. Energy storage, and in particular storage of hydrogen or methane produced from renewable resources, is another area of research in renewable energy where transformative research is critical. Clathrate hydrates, with as much as 164 volumes of gas contained per volume of clathrate hydrate, present a potentially attractive class of energy storage compounds. A second class of clathrate structures is the class of metallo-silicon clathrates. Although the structural and electronic properties of these cage-like structures of Si have been studied extensively, little is known about intercolation of methane or hydrogen within the clathrate channels. We have recently succeeded in storing up to 1 wt. % of hydrogen in a silicon clathrate material.

In addition to the two research groups, funds were used to support "seed" grants on promising but very preliminary research projects. Three projects funded in 2010 were entitled: "Enabling mechanical testing of fuel cell membranes in operational environments". "Synthesis and Assembly of Hybrid Polymer/Nanorod-Quantum Dot Structures", and "Charging Lithium Ion Batteries with New Cathode Materials of Iron Oxyfluoride FeOF Nanostructures.

Principal Senior Investigators	**Funding from CHECRA**
P. Craig Taylor, Director	$25, 000
Reuben Collins, Associate Director and Head IRG1	$150,000
Andrew Herring, Head IRG2	$125,000
Carolyn Koh, Head, Seed Grant Program and Head IRG3	$100,000

The manner in which each principal person or entity applied the funding in connection with the project

P. Craig Taylor: Discretionary funding of promising new research directions.
Reuben Collins: Funding for ordered arrays of silicon nanowires for improved solar cell materials
Andrew Herring: Funding for hybrid (organic-inorganic) nanostructured membranes for fuel cell and battery applications
Carolyn Koh: Funding of novel approaches to new materials for photovoltaic applications or membrane technologies. Funding of hydrogen storage in clathrate materials.

Results achieved

Center scientists and engineers have succeeded in growing nanometer sized dots and wires of silicon by several different techniques. These techniques include both gas phase growth and liquid solution phase growth. These dots and wires were characterized to analyze their potential for use in solar cell applications. Characterization methods have included measuring the optical absorption of light, measuring the electrical conductivity, and characterizing the defects in the various materials. Some of these materials, in particular the silicon wires, are currently being tested in photovoltaic devices.

The transport of ions, such as positively charged hydrogen, in nanostructured films of mixed polymeric and inorganic (oxide) components has been studied to determine the potential use of these films as membranes in fuel cells, batteries, electrolyzers, and other renewable energy devices. We have used the electric fields generated by ions in dissimilar materials to enhance the ionic conductivities of complex membranes. The characterization methods mentioned above have also been employed to study the membrane materials.

Center scientists have shown that a novel form of ice that forms only under pressure is capable of storing more methane or hydrogen than in most other structures. They have also been able to store hydrogen in a similar structure that is made from either silicon dioxide and silicon. These materials are currently being used to test how much hydrogen can be stored and how easily it can be extracted. To date Center members have succeeded in storing up to 1 wt. % of hydrogen in a silicon clathrate structure.

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"A Semiconducting graphene allotrope", D. J. Appelhans, **Z. Lin** and **M. T. Lusk**, Physical Review B, **82** 073410-1-7 (2010).

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"Two-dimensional carbon semiconductor: density functional theory calculations", D.J. Appelhans, L. Zhibin, **M.T. Lusk**, Phys. Rev. B **82**, 073410 1-4, 2010.

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"Nanocrystalline structure of nanobump generated by localized photoexcitation of metal film", D.S. Ivanov, L. Zhibin, B. Rethfeld, G.M. O'Connor, T.J. Glynn, L.V. Zhigilei, J. Appl. Phys. **107**, 013519 1-7, 2010.

"Facile abstraction of hydrogen atoms from graphane, diamond, and amorphous carbon surfaces: a first-principles study", B.N. Jariwala, C.V. Ciobanu, **S. Agarwal**, Phys. Rev. **B 82**, 085418 1-7, 2010.

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APPENDIX C

Liquid Crystal Materials Research Science Engineering Center
University of Colorado – Boulder
CHECRA Grant: $400,000 (per year for 6 years)

Summary: The Liquid Crystal Materials Research Center (LCMRC or the Center) has existed on the University of Colorado – Boulder campus since the early 1980s, with block funding from the NSF Division of Materials Research since September 1998. The LCMRC is currently funded as an NSF Materials Research Science and Engineering Center (MRSEC), one of an elite national network of advanced materials research programs.

Description of the project, the principal persons or entities involved in the project, and the amount of funding allocated to each principal person or entity

A major theme of materials science as we enter the 21st century is understanding and manipulation of the interactions between self-organizing complex molecules. It is precisely here that the study of liquid crystals has the greatest impact. Nowhere else are the requirements for understanding the delicate interplay between molecular architecture and its macroscopic manifestations more demanding than in the directed design of liquid crystals.

The Liquid Crystal Materials Research Center is one of the principal centers of liquid crystal study and expertise in the world, its research spanning the range from cutting-edge, basic liquid crystal and soft materials science to the development of enhanced capabilities for commercially important electro-optic, nonlinear-optic, chemical, biological, and other novel applications. The Center is a unique venue worldwide for research on key aspects of liquid crystal science and technology, chief among these the science and application of ferroelectric liquid crystals. The core Center research program is at the University of Colorado, Boulder.

The Center's research is organized within an Interdisciplinary Research Group addressing three major project themes: 1) understanding the relationship between molecular structure and macroscopic materials structure and properties of liquid crystals; (2) inventing new and useful ways of controlling liquid crystal behavior through interaction with surfaces; and (3) inventing and exploring new polymer materials possessing unique properties deriving from liquid crystallinity. Each of these research themes integrates *molecular modeling and design, chemical synthesis, physical studies,* and *applications development* into a multidisciplinary, collaborative research effort.

In 2010, the CHECRA funding was allocated to the three focus areas of the center described in this summary – science, administration, and outreach (in particular industrial and K-12 outreach).

Research - The past year of MRSEC, with NSF funding supplemented by the CHECRA matching state funds, has continued in its role as CU Boulder's single most visible materials research group nationally and internationally. Highlights of CHECRA funding include discovery of a new high-performance ionic liquid crystal-based electrolyte for lithium ion batteries and observation of a new polar liquid crystal phase with high symmetry, accepted for publication in the prestigious journal *Science*.

The MRSEC research program has enabled the campus to attract Assistant Professor Ivan Smalyukh, a superb young liquid crystal physicist, working in the liquid crystal nanophotonics area (project theme 1), and get his research program off to a very successful start.

Industrial Outreach - A principal industrial interaction highlight was the successful organization of the Liquid Crystals for Organic Photovoltaics (LCOPV) workshop, co-organized with the Colorado School of Mines renewable energy MRSEC and held in August, 2010 on the Boulder campus. The workshop featured an outstanding international slate of speakers, and brought researchers together from NREL, Colorado School of Mines, and Boulder. This program has stimulated a variety of new interactions between NREL and UCB research groups.

The Colorado high tech industry community continues to benefit from the Center. Center graduate students and postdocs have taken jobs in several local companies, including the R&D group at RealD, which recently gained recognition for providing the technical underpinnings of the modern 3D movies, including Avatar. A Center graduate (Chair of the Center Technology Advisory Board) is working in Boulder County in the R&D group for Serious Materials, with the goal of improving on the Serious Materials world-class energy efficient windows. Serious Materials has just received the contract to replace the windows of the Empire State Building (~ 6,000 windows).

The Center has been a major innovator in the field of ferroelectric liquid crystals (FLCs) for many years. Displaytech, Inc., a Colorado company founded by the Center PI and Co-PI, and dedicated to commercialization of FLCs, was recently acquired by Micron Technology, Inc., headquartered in Idaho. The Displaytech team continues to work in their labs and offices in Longmont, and recently commercialized upraded FLC microdisplays found in newly introduced 3M MPro 180 pocket projectors. The same device is being applied by Light Blue Optics, with headquarters in Cambridge, England, and offices in Colorado Springs, in a completely new kind of projector technology where the image is a two-dimensional hologram. These projectors are scheduled to become commercial in the immediate future.

Education Outreach - Highlights from the past year include expansion of the *Materials Science from CU* program, now one of CU's most effective K-12 outreach programs. In outreach to children (and parents), the focused attention of a dedicated outreach Director has enabled many notable successes over the past year. Examples include:

- *Materials Science from CU* has delivered **250** classes to **6,000** Colorado children, bringing Center personnel into the classroom using the understanding of materials to teach physical science concepts (**1,350** classes to **58,000** students over the past 10 years).

- The *Liquid Crystals Wizards* science-for-kids show continues with the Center's eleventh presentation, in March, 2011 (presented to more than **2,400** K-6 children and parents over the past 10 years).

- Center senior investigator participated\\ion in a variety of high school and undergraduate research experience and undergraduate/graduate minority access programs in 2010.

- NSF Partnership for Research and Education in Materials (PREM) funding for support of undergraduate and graduate research opportunities for minority students.