COLORADO HIGHER EDUCATION COMPETITIVE RESEARCH AUTHORITY

University of Colorado:Colorado State University:University of Northern Colorado:Colorado Schools of Mines:State of Colorado

March 13, 2009

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 2008.

In 2007, the Authority pledged $400,000 per year for six years to each of two proposals submitted to the National Science Foundation (NSF) for Materials Research Science and Engineering Centers (MRSECs), which support interdisciplinary materials research and education while addressing fundamental problems in science and engineering. NSF selected both Colorado MRSEC proposals for these highly competitive awards.

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 Center has spun off six companies, contributing significantly to the region's and state's economic development goals. The Authority made the first year payments of $400,000 to each of these Centers.

In 2008 the Authority also decided it was important to honor a prior, but suspended commitment to the NSF to support the Extreme Ultraviolet Engineering Research Center at Colorado State University (a collaboration with the University of Colorado). The Authority made the first of two pledged annual payments of $200,000.

Attachments A-C have more detailed information on each of the three projects funded in 2008.

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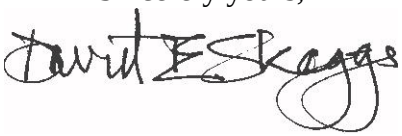
During calendar year 2008, the Authority received quarterly distributions from the waste tire recycling fees totaling $310,365. Interest earnings on those funds and the prior year's receipts totaled $24,774, for a total income of $335,409 in 2008. As described above, the Authority distributed $1,000,000 in matching grants. The Authority fund balance on December 31, 2008 was $165,928.

Please contact me if you have any questions.

Sincerely yours,



David E. Skaggs

cc: Michael Poliakoff
William H. Farland
John Poate
Robbyn Wacker

Attachment A

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.

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). The first is a high-risk but potentially high-pay-off initial seed project. 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. The initial Seed project 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.

Principal Senior Investigators	**Funding from CHECRA**
P. Craig Taylor, Director	$25, 000
Reuben Collins, Head IRG1	$150,000
Andrew Herring, Head IRG2	$150,000
Carolyn Koh, Head, Seed Grant Program	$50,000

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 the storage of fuels, such as hydrogen and methane

Results achieved

Center scientists and engineers have succeeded in growing nanometer sized dots of silicon by several different techniques. These dots will be characterized to analyze their potential use in solar cell applications.

Center scientists and engineers have succeeded in growing nanostructured films of mixed polymeric and inorganic (oxide) components. The transport of ions, such as positively charged

hydrogen, will be studied to determine the potential use of these films as membranes in fuel cells, batteries, electrolyzers, and other renewable energy devices.

Center scientists and engineers have succeeded in growing a novel form of ice that may be capable of storing more methane or hydrogen than in more common structures of ice. They have also been able to store hydrogen in a similar structure that is made from silicon. These materials will be used to test how much hydrogen can be stored and how easily it can be extracted.

Attachment B

Engineering Research Center in Extreme Ultraviolet Science and Technology
University of Colorado
Director: Prof. Jorge J. Rocca. Colorado State University
Deputy Director: Prof. Margaret M. Murnane
CHECRA Grant: $200,000

Project Summary

The National Science Foundation (NSF)-funded Extreme Ultraviolet Science and Technology Engineering Research Center 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 $200K provided by the Colorado Higher Education Competitive Research Authority (CHECRA) assisted the Center in making very good progress in technical areas in which the Center has brought to Colorado nearly $8 million in federal grants during 2008.

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

Light in the Extreme Ultraviolet (EUV) region of the spectrum (wavelengths approximately 2 to 50 nm) is becoming 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 surface, chemical, and materials dynamics studies, EUV nonlinear optics, biological studies, 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 industrial corporate members whose number has increased to 18 in 2008.

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 are

combining them with advanced EUV optics to implement engineered systems designed to solve challenging engineering and scientific problems. Breakthroughs in 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 several engineered systems will lead to 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 the development of compact EUV microscopes with sub-38 nm resolution, a laser ablation testbed capable of producing sub-100 nm holes, a photoacoustic metrology testbed with femtosecond temporal resolution and 750 nm spatial resolution, a new high-order x-ray Raman spectroscopy tool for observing ultrafast molecular motions, a single photon ionization spectrometer for the study of nanoclusters, a table-top workstation for the patterning of arrays of nanostructures , and 15 nm resolution imaging of magnetic nanoparticles. Three-D tomographic imaging of yeast cells at somewhat reduced resolution were demonstrated with synchrotron radiation. In the past year we have achieved record resolution for lensless imaging systems (70 nm), and for a compact full field microscope capable of imaging with a single shot from a desk-top size EUV laser source (54nm).

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 scientist, several of which have now graduated and joined industries in Colorado. Our Research Experience for Undergraduate program has already mentored 107 students, with nearly 50% of its summer participants from under-represented minority groups. We have also developed a successful set of workshops for K-12 students and teachers.

In the past two years we have significantly increased the number of high school student researchers participating in Center research, and during the last year we established 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. 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 manner in which each principal person or entity applied the funding in connection with the project and results achieved

The $200K in state matching funds to the Center for 2008 partially supported young scientists who worked at in collaboration at Colorado State University and the University of Colorado to develop new sources of EUV laser light. These new light sources are now 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, $100K of the CHECRA matching funds were mostly used to partially support two post-doctoral students and a young research scientist. They worked in the development of an EUV laser that will be used to enable future advances in ultra-high resolution microscopy and in the nanopattering of materials. In 2008 a microscope that uses an EUV light source previously developed by the Center received an R&D 100 award as one of the most significant technology innovations of the year.
The advances achieved in the past year in both new laser source development and applications[1-7] can be expected to enable advances in nanotechnology, the development and characterization of new materials, the storage of hydrogen for clean energy delivery, the diagnostics of dense plasma of interest for the generation of energy by nuclear fusion, the imaging of biological samples, and other areas.

The University of Colorado used their $100K State Matching funds for the NSF EUV ERC to partially support 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.[8-13] Many applications of these technologies are anticipated in the next several years 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 industry; measurements of heat transport in nanostructures of interest to nanoelectronics and photovoltaics; imaging at the molecular level using compact x-ray sources; and understanding and optimizing magnetic materials on nanoscale dimensions for applications in data storage. Past work on laser and x-ray sources has already been commercialized and has led to a 23-person spin-off company in Boulder. The current work will also be commercialized in the future.

Summary to Benefits to the State of Colorado in 2008

During 2008 the Center:

- Generated nearly $ 8 M in funding from Federal Agencies for Colorado State University and University of Colorado;
- Supported ~ 50 graduate students, undergraduate students, post-doctoral students, and faculty in Colorado;
- Graduated numerous students with PhD or MS degrees who were hired by Colorado high technology companies (e.g., Avago, Brooks Automation, KM Laboratories, InPhase);
- 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;
- Provided summer research experiences for middle school teachers and high school students;
- Reached more than 1000 K-12 students and teachers with science workshops and demonstrations;
- Increases the National and International reputation of Colorado as a leader in advanced technology and science.

Selected resulting Center publications

1. Y.. Wang, M. Berrill, F. Pedaci, M.M. Shakya, S. Gilbertson, Zenghu Chang , E. Granados, B.M. Luther, M. A. Larotonda, J.J. Rocca, "Measurement of 1 Picosecond Soft X-Ray Laser Pulses from an Injection-Seeded Plasma Amplifier," Physical Review A, 79, 023810, (2009).

2. F. Brizuela, Y.Wang, C.A. Brewer, F. Pedaci, W. Chao, E.H. Anderson, Y. Liu, K.A. Goldberg, P.Naulleau, P. Wachulak, M.C. Marconi, D.T. Attwood, J.J. Rocca, and C.S. Menoni, "Microscopy of extreme ultraviolet lithography masks with 13.2 nm tabletop laser illumination," Optics Letters, 34, 271, (2009).

3. F. Pedaci, Y. Wang, M. Berrill, B. Luther, E. Granados, and J.J. Rocca, "Highly coherent injection seeded 13.2 nm table-top soft x-ray laser," Optics Letters 33, 491, (2008).

4. C.A. Brewer, F. Brizuela, P. Wachulak, D.H. Martz, W. Chao, E.H. Anderson, D.T. Attwood, A.V. Vinogradov, I.A. Artyukov, A.G. Ponomareko, V.V. Kondratenko, M.C. Marconi, J.J. Rocca, and C.S. Menoni, "Single shot extreme ultraviolet laser imaging of nanostructures with wavelength resolution," Optics Letters 33, 518, (2008).

5. P.W. Wachulak, M.G. Capeluto, C.S. Menoni, J.J. Rocca, and M.C. Marconi, "Nanopatterning in a compact setup using table top extreme ultraviolet lasers," Opto-Electronics Review, 16, 444, (2008).

6. R.L. Sandberg, C. Song, P.W. Wachulak, D.A. Raymondson, A. Paul, B. Amirbekian, E. Lee, A.E.Sakdinawat, C. La-O-Vorakiat, M.C. Marconi, C.S. Menoni, M.M. Murnane, J.J. Rocca, H.C. Kapteyn, and J. Miao, "High Numerical Aperture Table Top Soft X Ray Diffraction Microscopy with 70 nm Resolution," Proceedings of the National Academy of Science, 105, 24, (2008).

7. Y. Wang, E. Granados, F. Pedaci, D. Alessi, B. Luther, M. Berrill, and J.J. Rocca, "Phase coherent table top soft x-ray lasers at 18.9 nm and 13.9 nm by saturated amplification of high harmonic pulses in Nickel-like ions," Nature Photonics, 2, 94, (2008).

Attachment 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).

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 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.

The core Center research program is organized at the University of Colorado, with additional Senior Investigators at the University of Utah and the Colorado School of Mines.

In 2008, 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).

Results achieved

The past six years of MRSEC funding had a profound impact on both the Center and the University of Colorado. This work has continued with the 2008 NSF funding and the CHECRA matching state funds.

The MRSEC stimulated the creation of CU faculty lines which enabled the campus to attract two additional leading liquid crystal research groups to the Center: those of Daniel Schwartz and Douglas Gin. These world-class investigators significantly enhance the Center's research capability and breadth, particularly in the *Interface* & *Polymer/Gel* areas.

The past 6 years have been highlighted by the creation of *Materials Science from CU*, 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 6 years. Examples include:

- The Center's key K-12 outreach program, *Materials Science from CU*, which has delivered **1,100** classes to **52,000** Colorado children, bringing Center personnel into the classroom using the understanding of materials to teach physical science concepts;
- The *Liquid Crystals Wizards* science-for-kids show, presented to more than **2000** mostly K-6 children and their parents'
- Participation in a variety of high school and undergraduate research experience and undergraduate/graduate minority access programs; and
- US Department of Education Graduate Assistantships in Areas of National Need funding for a Graduate Program in Liquid Crystal Science and Technology.

Finally, the Center faculty and students have contributed to Colorado's high tech industry by creation and nurturing of a robust and vibrant community of LC scientists and engineers, currently working in 12 Colorado Corporations dedicated to commercialization of unique LC and other "soft materials" technology. Industrial outreach activities of the Center range from the founding of new companies, to the training of students for high tech materials science-related jobs in Colorado. The Center's roots focus on FLCs, which due to the concerted effort of Center personnel, are now entering wide commercial application driven by Colorado Companies. The LCMRC continues to aggressively pursue its role as a resource for FLC industrial development, conducting collaborative research programs with a variety of companies. This research focuses on critical materials issues of direct relevance to the commercialization of FLCs.