PIONEERING the FUTURE

APPLIED PHYSICS AND MATERIALS SCIENCE AT CALTECH

The Materials Science and Applied Physics options at Caltech offer multi-disciplinary graduate programs spanning engineering and the applied sciences in which fundamental physical principles are used to address research issues of technological importance at the frontiers of engineering and science. Research in these broadly defined fields encompass diverse topics including photonics and optoelectronics, biophysics, materials for energy storage and conversion, solid-state electronic materials and devices, electroceramics, plasma physics, amorphous and nanostructured materials, and structural materials.

Applied Physics at Caltech is built on the foundations of quantum mechanics, statistical physics, electromagnetic theory, mechanics, and advanced mathematics. Materials Science, while sharing the philosophy of a strong foundation in physical sciences, places emphasis on the thermodynamics and kinetics of the solid state. The style of research in both programs is simultaneously theoretical and richly experimental. State-of-the-art facilities are housed in Keck, Watson and Steele Laboratories and in associated laboratories across campus.

The Materials Science option broadly links the physics and chemistry of the solid state to materials of engineering relevance, spanning length scales from the atomistic to large-scale structural components. Accordingly, the option has strong ties to faculty in Applied Mechanics, Mechanical Engineering, Chemistry, Chemical Engineering, and, of course, Applied Physics. The Applied Physics option* is designed to connect what are conventionally considered “engineering” and “pure physics” disciplines. To effectively exploit the advances that can be made at the boundaries between these overlapping disciplines, the Applied Physics option draws its faculty from the divisions of Physics, Mathematics and Astronomy; Engineering and Applied Science; Chemistry and Chemical Engineering; and Geological and Planetary Sciences. This interdivisional aspect of our programs allows a flexibility and range in curriculum that results in an extraordinary mixture of courses and research in different divisions. In fact, one of the unique aspects of Caltech is that research and collegiality extend across departmental and divisional borders; and the subsequent collaborations are nothing short of spectacular.

Graduates of Caltech’s Applied Physics and Materials Science options can be found among the faculties of leading universities and among the technical management and engineering staffs of the foremost technology companies, ranging from established industry leaders to early stage start-up companies, some of which have been founded by Caltech faculty members.

While our efforts are motivated primarily by the research interests of individual faculty, interdisciplinary center programs also provide a strong research and educational infrastructure. The NSF Center for the Science and Engineering of Materials (CSEM) addresses both research and educational aspects of polymeric, structural, photonic, and ferroelectric materials that will be necessary to solve critical societal needs of the 21st century. The Center pioneers a number of exotic and futuristic materials and applications such as microphotonic materials and devices, integrated ferroelectrics, macromolecular engineering, as well as research at the interfaces between these fields. The CSEM effort in Mesophotonic Materials is motivated by advances in the synthesis and theoretical understanding of materials designed to manipulate light on scales at and below the wavelength of light. These efforts will produce near-term advances in microphotonics and move into the revolutionary domain of devices on scales of tens of nanometers. Caltech’s NSF Center for Neuromorphic Systems Engineering (CNSE) seeks to give senses and sensory behavior to machines by understanding the biological basis for vision, olfaction, hearing, touch, learning, decision making, and pattern recognition, and enabling fabrication of integrated photonic and electronic devices which allow artificial systems to perform these functions. The NSF Institute for Quantum Information (IQI) further supports our work with its aim of understanding how fundamental physical laws can be harnessed to dramatically improve the acquisition, transmission, and processing of information.

http://www.aph.caltech.edu
http://www.matsci.caltech.edu

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*Caltech’s Applied Physics option was rated No. 1 in the United States in a recent issue of the Gourman Report guide to graduate programs.

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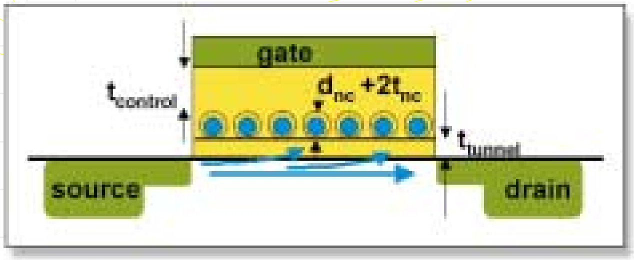
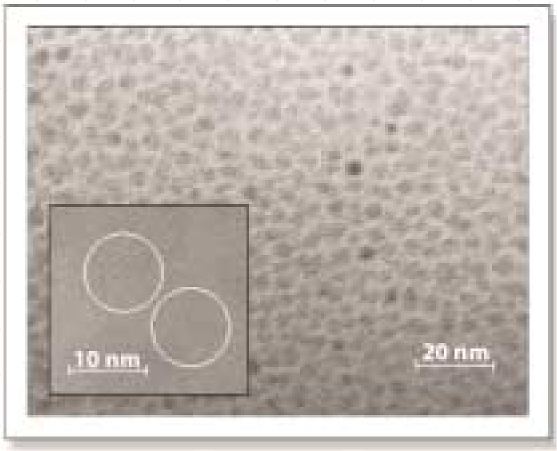
MATERIALS and STRUCTURES for NANO DEVICES: BEYOND VLSI

HARRY ATWATER





Left image: transmission electron micrograph of silicon nanocrystal array that forms the floating gate of the nanocrystal nonvolatile memory device depicted schematically at upper right. Nanocrystals are formed via gas-phase nucleation and growth as an ultrafine aerosol that is subsequently deposited in the device's active region. Using this approach, we have fabricated nanocrystal memories which are among the highest performance nonvolatile memory structures developed to date.

Professor Atwater's group is interested in electronic and photonic materials for use in future functional devices. Device materials research is interdisciplinary, involving theoretical and experimental issues spanning applied physics, physics, materials science, chemistry, and electrical and chemical engineering.

Nanostructure Electronics and Photonics

In the mesoscopic size regime, materials have size-tunable properties intermediate between those of single atoms and bulk solids. We are studying group IV semiconductor (Si and Ge) nanocrystals that behave electronically as 'quantum dots,' including nanoscale synthesis, interface passivation, excited state decay, and localized state carrier transport. We have also recently developed a Si nanocrystal memory that is one of the highest performance nonvolatile memories created to date. At the nanoscale, optical materials are dominated by near-field interactions. Electromagnetic energy transport can occur below the diffraction limit in nanoscale waveguides called "plasmon wires" that consist of chains of closely spaced metal particles yielding structures with optical functionality that cannot be obtained in other ways at a length scale << 1 micron. Currently we are fabricating nanoscale plasmon waveguides and assessing their photonic performance with near-field optical microscopy.

Photovoltaics

We are exploring two approaches to photovoltaics, the direct generation of electric power from sunlight, including designs with either ultrahigh efficiency or very low cost. Advances in semiconductor wafer engineering enable us to create structures with potential to achieve world-record energy conversion efficiency (40–50%) in AlInGaP/GaInAsP/InGaAs/Ge heterostructure solar-cell designs. To achieve very low-cost cell designs, a crystalline silicon thin film (1–30 microns) is grown at low temperatures with large grain sizes on inexpensive substrates.

Active Oxide Materials

Epitaxial complex oxide films of $BaTiO_3$ and related materials have interesting electromechanical and photonic device possibilities related to their piezoelectric, ferroelectric, and photorefractive properties. Integration of these materials in single crystal form with conventional electronics is difficult. A new approach based on oxide film growth on biaxially textured pseudosingle crystalline magnesium oxide (MgO) templates enables a path to integration of epitaxial oxide films on amorphous substrates such as glass.

http://daedalus.caltech.edu/

3D TOPOLOGICAL DYNAMICS of MAGNETIZED PLASMAS

PAUL BELLAN

Paul Bellan and his group are studying the 3D topological dynamics of magnetized plasmas. This study is relevant to two radically different applications that, curiously, are governed by essentially the same physics. The first application is the eruption of solar prominences, huge twisted plasma-filled magnetic flux tubes that protrude from the sun's surface. Not only are these eruptions an intriguing mystery in themselves, but they also are of important practical significance because the powerful plasma blasts they eject can, on rare occasions, damage or destroy spacecraft and induce large currents in terrestrial electrical power grids. These large currents can cause grid failure plunging millions of people into darkness. The second application is the development of the spheromak concept, a 3D vortex-like laboratory plasma configuration that self-organizes out of turbulent instabilities. The spheromak offers a potentially attractive and low-cost method for confining the high-temperature plasma required for controlled thermonuclear fusion.

Laboratory simulation of solar prominence.

Spheromak initiation using planar magnetized plasma source.

We have been exploiting the relationship between solar prominence and spheromak physics in laboratory experiments. These experiments involve specially designed plasma guns that eject multi-megawatt pulses of magnetized plasma into a large vacuum chamber. The magnetic forces driven by the tens or hundreds of kiloamperes of current easily overwhelm all other forces (e.g., gravity, hydrodynamic pressure) so that the plasma assumes a shape dictated by the three-dimensional interaction of topologically complex magnetic fields. The solar prominence simulation and spheromak experiments differ mainly in the prescribed symmetry of the initial magnetic field and current flow pattern.

The solar prominence simulation experiment takes place at a billion-fold reduction in both time and space scales compared to solar eruptions (microseconds versus minutes and tens of cm versus 100,000 km). Nevertheless, the laboratory simulation replicates the solar dynamics because the relevant dimensionless parameters and topology are similar. Erupting twisted, arch-shaped plasmas have been produced and their dynamics have been investigated to provide insights regarding solar eruptions.

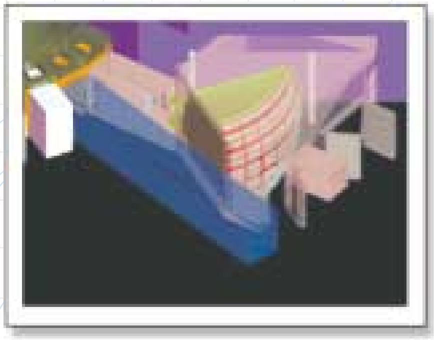
The spheromak experiment involves an advanced coaxial magnetized plasma source that creates vortices of magnetized plasma in a controlled manner. Unlike previous spheromak sources, the new source has a planar geometry which provides greater efficiency and also makes diagnostic access more straightforward. The planar spheromak has topology and dynamics analogous to the accretion disks associated with black holes; we plan to investigate this relationship.

The plasmas in both experiments are diagnosed using intensified gated CCD cameras with nano-second shutter speeds, laser-induced fluorescence, magnetic probes, and other advanced methods. Associated theoretical activities are also underway. These include three-dimensional numerical modeling of solar eruptions and investigations of the excitation of magnetohydrodynamic waves (Alfven waves) that occur when the plasma abruptly lowers its magnetic energy by changing its magnetic topology.

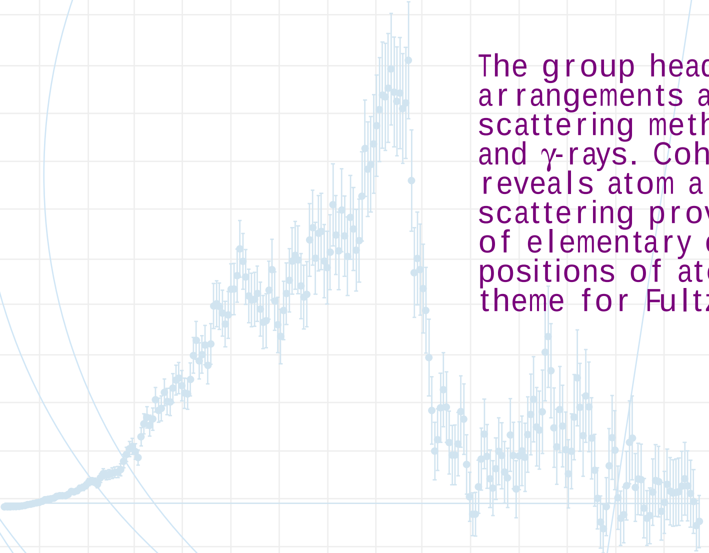
http://ve4xm.caltech.edu/Bellan_plasma_page/

the DYNAMICS and ARRANGEMENTS of ATOMS

BRENT FULTZ



Schematic drawing of the ARCS spectrometer proposed for construction at the Spallation Neutron Source. Red grid holds detector tubes, open doors towards right show scale. Fultz is the principal investigator on a proposal to build the inelastic neutron instrument depicted in the figure.



The group headed by Brent Fultz is studying the arrangements and dynamics of atoms in materials by scattering methods using x-rays, electrons, neutrons, and γ-rays. Coherent elastic scattering, for example, reveals atom arrangements. Coherent inelastic scattering provides the energy-wavelength relationships of elementary excitations in solids. Identifying the positions of atoms and their movements is a general theme for Fultz and his group.

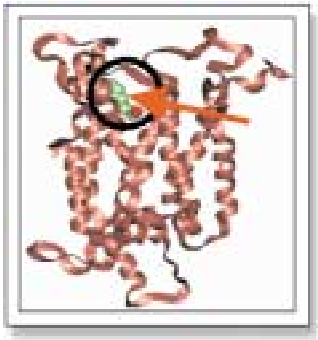
Most of what we know about atom arrangements in materials comes from diffraction measurements, where an incident plane wave is directed into a sample and the angles and intensities of the out-going diffracted waves are detected. Fultz's group is exploring the novel method of γ-ray diffraction, in which an incident γ-ray is absorbed by identical nuclei in a crystal. The decay of this nuclear excitation creates a new γ-ray photon with the angular distribution of a diffraction pattern. The physical process of scattering is fundamentally different from that of x-ray diffraction, and therefore offers new opportunities for studies of the atom arrangements in materials. For example, we are using the chemical spectroscopic information of Mössbauer spectra to control the phase and intensity of wave emission from selected nuclei in a sample.

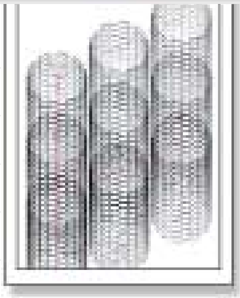
A major thrust of our research is investigating how atom vibrations affect the entropy and thermodynamic stability of materials. The concept of "vibrational entropy" is new to the materials science community, and its importance was unexpected. Our group is now measuring phonon spectra of materials by inelastic neutron scattering to understand the reasons for differences in vibrational entropy of different solid phases. Recent studies have identified effects on vibrational dynamics from chemical disorder and local distortions around impurity atoms. The field of inelastic neutron scattering is a broad one, and a field that will grow in the United States with the construction of the Spallation Neutron Source.

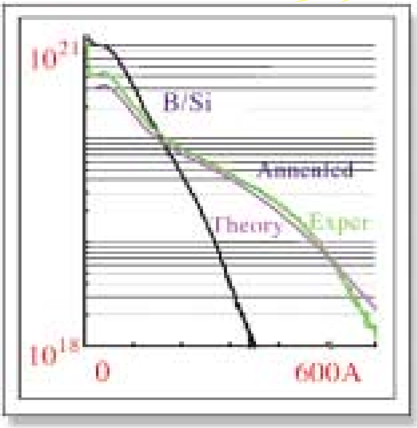
http://www.caltech.edu/~matsci/btf/Fultz1.html

MATERIALS and PROCESS SIMULATION CENTER

WILLIAM A. GODDARD III







The Hierarchical Multiscale strategy is used by the Goddard group to connect first principles simulation and design of materials with macroscopic manufacturing and characterization. Applications include sensors (illustrated is $C_9H_{19}OH$ bound to an olfactory receptor), nanotechnology (an array of bucky tubes is shown), and processing (diffusion of B in Si).

The goal of the research in Professor Goddard's group (the Materials and Process Simulation Center or MSC in the Beckman Institute) is "de novo" or first principles engineering. They develop theory and simulation tools to predict the fundamental properties of materials and of manufacturing processes. To connect the enormous range of scales from angstroms to yards and from femtoseconds to years, they use a hierarchy of simulations which start with quantum mechanics (electrons), and move through a sequence of successively coarser levels, each using parameters and concepts averaged from the finer levels. His students obtain degrees in chemistry, materials science, physics, applied physics, chemical engineering, biochemistry, and biology.

Our goal is to describe the properties of chemical, biological, and materials systems directly from first principles (without empirical data). Our strategy is to build from quantum mechanics (QM) to practical engineering design and processing through a hierarchy of more approximate methods suitable for longer length and times scales as indicated above, including molecular dynamics (MD) and mesoscale dynamics, to connect ultimately to macroscopic dynamics.

Our research is equally focused on developing new methods and on applying these methods to applications important in the industrial and commercial sectors. Our method development focuses on extending the methods of QM and MD to higher accuracy on larger systems, on developing the connections from QM to MD that describe reactions, and on averaging atomic quantities to describe the meso scale. The new methods, validated by application to problems, are well characterized experimentally.

We then apply these methods to critical problems in chemical, biological, and materials systems. Current research efforts are directed to the following materials, among others: Semiconductors (dopant diffusion in nanoscale Si, properties of Si/SiO_2 interface, epitaxial growth of GaN); Ceramics (structures, phase diagrams, catalysts); Metal Alloys (plasticity, dislocations, crack propagation, spall, glass formation); Polymers (structures and properties of dendrimers, gas diffusion, surface tension); and Biochemical Materials (structure and function of proteins, non-natural amino acids for biopolymers).

The applications of our work have proven useful in a variety of domains, including catalysis (methane activation, metathesis, ammoxidation of alkanes), nanotechnology (carbon nanotubes, bio-nanotechnology), and environmental engineering (selective encapsulation, humic acid, particulates).

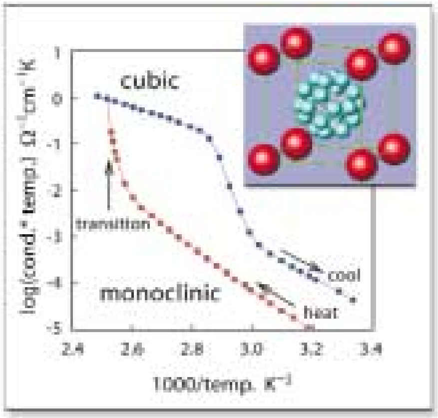
Most of our projects involve collaborations with experimentalists at Caltech, other universities, national laboratories, and industry.

http://www.wag.caltech.edu/

SOLID STATE IONICS and ELECTROCERAMICS

SOSSINA HAILE

A single-cell fuel cell comprised of graphite electrodes, embedded with Pt catalyst particles, on either side of the solid electrolyte, cesium hydrogen sulfate —otherwise fondly known as the "power pellet."



The conductivity of α-$Cs_3(HSO_4)_2(H_2PO_4)$ as a function of temperature. Notice the sharp increase as the material transforms from its monoclinic to cubic (disordered) phase. The inset shows a model of the high-temperature structure. Notice also the significant hysteresis in the transition behavior.

Sossina Haile's research centers on ionic solids, with the objectives of understanding the fundamental mechanisms that govern ion transport and structural phase transitions, and applying such an understanding to the development of advanced solid-state electrochemical and electroactive devices.

Within the broad range of ionically conducting solids, we have concentrated on two classes of proton conductors, oxyanion-based acid salts and oxide perovskites. Amongst electroactive ceramics, we are most interested in ferroelectric perovskites that exhibit large structural distortions at the ferroelectric transition. In addition, we have initiated a program in thermoelectric materials. In all cases, the over-riding goal is to relate crystal-chemical and microstructural features, which in many cases can be manipulated by novel processing routes, to macroscopic material behavior. Advances at this fundamental level will enable a broad range of energy technologies, from thermal-to-electric converters to high efficiency batteries and, most relevant to our work, fuel cells.

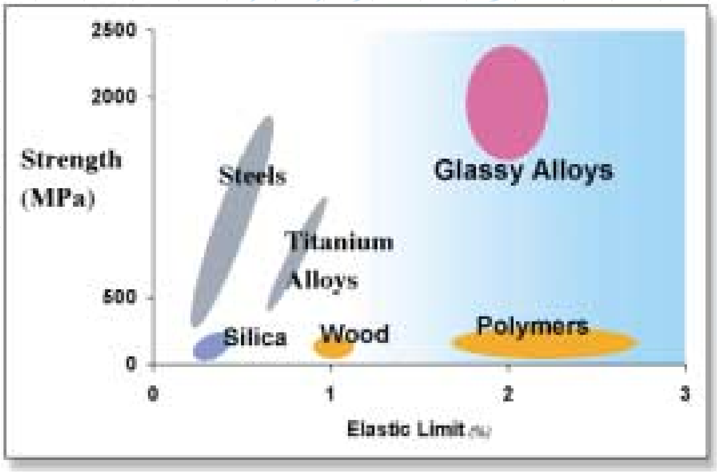
As an example of the flavor of research carried out in the Haile group, the program on acids salts is described here. Acid salts (or solid acids) are an intriguing class of compounds with chemical properties intermediate between those of a normal salt (e.g. Cs_2SO_4) and a normal acid (e.g. H_2SO_4). Upon heating several alkali acid salts of sulfates and selenates undergo structural transitions (often termed "superprotonic") to disordered phases that lead to unusually high proton conductivity (10^{-3} – 10^{-2} S/cm). In order to understand the origin of this transition, and ultimately exploit it for technological purposes, we are exploring acid salts with a broad range of chemistries, from closely related inorganic phosphates, to more distant compounds containing organic cations. The list of new compounds that have resulted from this study includes $Cs_2Na(HSO_4)_3$, $Cs_2(HSO_4)(H_2PO_4)$, and $Cs_2(NH_3(CH_2)_2NH_3)(HSO_4)_4$ and continues to grow. While many exhibit superprotonic transitions, several, such as $Cs_2Na(HSO_4)_3$ do not, allowing us to propose crystal-chemical criteria for such a transition. We use a broad range of experimental techniques to characterize these materials, from conventional X-ray diffraction, to advanced solid state NMR methods, and neutron scattering techniques. These studies are complemented with atomistic simulations (in collaboration with Prof. Bill Goddard) that permit us to predict superprotonic behavior in new and even hypothetical compounds. To demonstrate the utility of solid acids for our increasingly energy dependent society, working fuel cell prototypes based on these materials have been built.

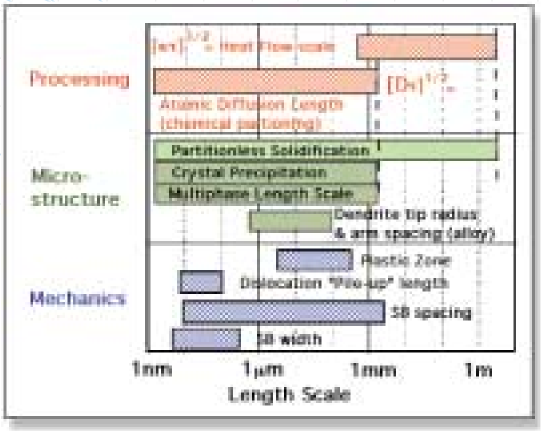
To learn more about our efforts in this and other areas you are invited to visit our website at the address given below.

http://addis.caltech.edu/Haile

NON-EQUILIBRIUM and METASTABLE MATERIALS

WILLIAM JOHNSON





Professor Johnson's group conducts research on non-equilibrium and metastable materials. During the past decade, they have developed unusual metallic alloys which fail to crystallize during solidification at low cooling rates, thus forming "bulk" glasses. Research on the liquid alloys includes fundamental studies of rheology, atomic diffusion, crystallization kinetics, liquid/liquid phase separation, and the glass transition. Research on the solid "glassy" materials includes studies of elastic properties, and mechanisms of deformation, flow, and fracture. The group has developed composite materials which employ a metallic glass matrix to achieve unusual combinations of properties for structural engineering applications.

Conventional metallic materials have a crystalline structure consisting of single crystal grains of varying size arranged in a microstructure. Such structures are produced by the nucleation and growth of crystalline phases from the molten alloy during solidification. By contrast, certain oxide mixtures (e.g., silicate glasses), have such sluggish crystal nucleation and growth kinetics, that the liquid can be readily undercooled far below the melting point of crystals (e.g., a quartz crystal). At deep undercooling, these oxide melts undergo a "glass transition" and freeze as vitreous solids. Our group has developed multicomponent metal alloys which vitrify with the same ease as observed in silicate melts. These bulk metallic glasses (BMGs) have unusual properties. They are typically much stronger than crystalline metal counterparts (by factors of 2 or 3), are quite tough (much more so than ceramics), and have very high strain limits for Hookean elasticity (see left-hand figure above). As a new class of engineering materials, BMGs offer an opportunity to revolutionize the field of structural materials with combinations of strength, ductility, toughness, and processability outside the envelope achievable using current technology.

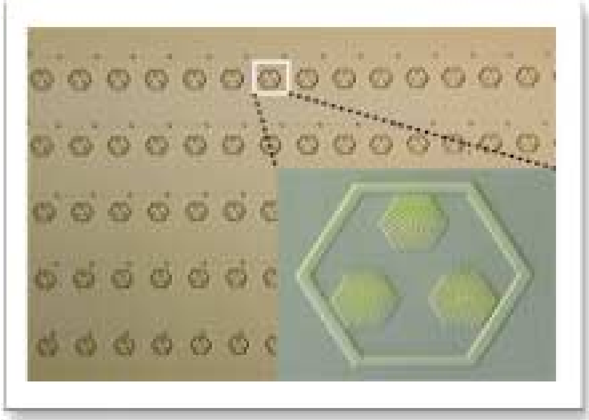
On the scientific side, the development of BMG alloys has made possible detailed fundamental studies of the undercooled liquid state and the glass transition in metallic systems. Quite unexpectedly, it has been found that the liquid BMG alloys exhibit atomic transport and rheological characteristics very different from simple metals and previously thought to be unique to oxide/silicate materials. Further, the traditional theory of crystal nucleation has been found to be inapplicable in these materials and the development of new theory based on chemical kinetics is in progress.

Professor Johnson is currently heading a multi-university DoD project to develop structural amorphous metal for use in such diverse areas as aircraft, autos, sports products, and medical implants. The project includes collaborations with several companies (e.g., Boeing and General Motors).

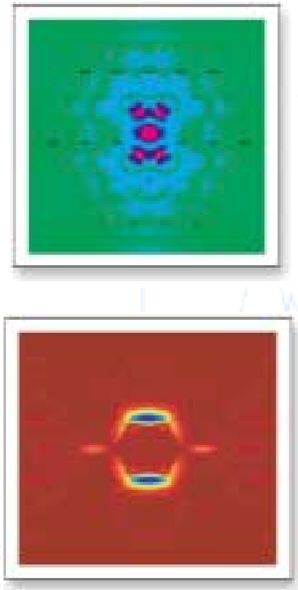
http://www.its.caltech.edu/~matsci/wlj/Johnson.html

ENGINEERING of the PHOTON: NANO-SCALE OPTOELECTRONIC DEVICES

OSKAR PAINTER



Above: An array of nanometer scale lasers formed in planar photonic crystals. Inset shows a magnified image of three lasers within the array, the very center region (barely visible) of each cavity representing the area to which the light is actually confined.



Left: Finite-difference time-domain simulation of a localized resonant mode in a hexagonal photonic crystal. Real Space (top) and Momentum Space (bottom).

The research in professor painter's group centers around the engineering of the propagation of light within materials to create new optoelectronic devices with increased functionality and density. Areas of current interest involve semiconductor lasers, microcavity physics, and planar lightwave circuits.

Current research efforts are focused on the interesting ways in which light propagates within microfabricated high-contrast periodic dielectric and metallic structures. The use of periodic structures to engineer electromagnetic wave propagation has a rich history dating back to some of the early work on microwave radar technologies during the Second World War and more recently to the design of Distributed Feedback Lasers and Fiber Bragg Gratings which have become integral components of the fiber-optic telecommunication industry. Today these ideas have been reborn in the form of photonic bandgap (PBG) materials or photonic crystals (PC), in which high-contrast periodic dielectric and metallic structures are used to create such strong dispersion as to open up frequency windows within which the propagation of light is entirely forbidden.

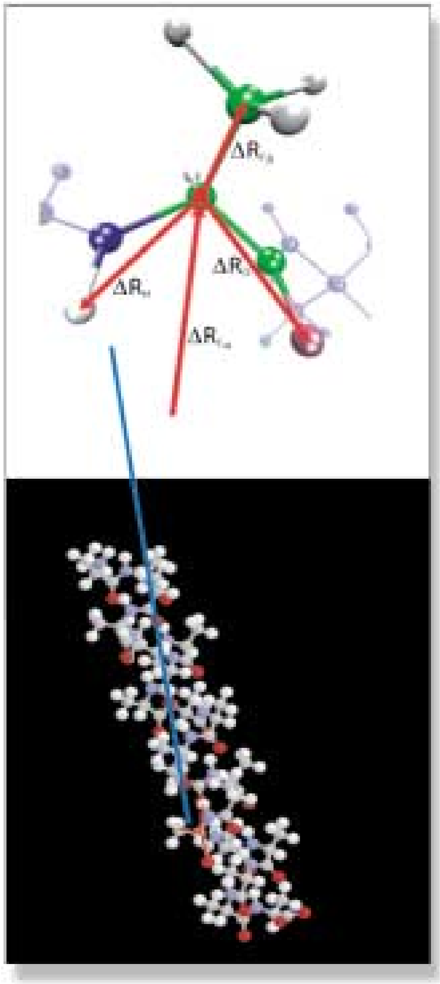
This new focus on optical PBG materials has spawned a great deal of interest in work on the control of light emission from materials placed within PBG structures. It has long been realized that the spontaneous emission of radiation from an excited state of matter depends critically upon the electromagnetic environment in which it is placed. One may thus imagine using PBG materials to significantly alter the way in which radiation is emitted from that in free space. Using a variety of micro and nano-fabrication techniques to create wavelength scale features in semiconductor materials we have been able to realize this goal. By forming optical cavities in which light is trapped within modal volumes approaching the theoretical limit of a cubic half-wavelength (some hundredths of a cubic micron), electrons and holes within the semiconductor material are forced, when they recombine, to emit light into a single resonant mode of the cavity. Ongoing projects involve the design, fabrication, and characterization of semiconductor laser sources based upon this technology, and more fundamental studies of the interactions of electrons and photons within these ultra-small volume single-mode optical cavities.

As with some of the earlier applications of periodic structures, our research group is also looking at utilizing the more fundamental aspects of photonic crystals, that being their dispersive properties. Present research involves the design and fabrication of different planar photonic crystal structures for wavelength division multiplexing (WDM) applications, non-linear optics, and high-density planar lightwave circuits.

http://www.aph.caltech.edu/people/painter_o.html

THE PHYSICS OF STRUCTURE and FUNCTION

ROB PHILLIPS



This figure shows one of several ways in which the Phillips group in collaboration with that of Klaus Schulten's group at the University of Illinois is attempting to construct "coarse-grained" representations of macromolecules. This figure shows the coarse graining of an alanine residue and the way that this residue fits into an alpha helix. The objective of this work is to build reduced models of macromolecular function which do not require full atomic resolution.

The group headed by Rob Phillips is building theoretical models of the connection between structure and function in the setting of both biological systems as well as traditional materials. One of the key theoretical tools used in the Phillips group is systematic coarse graining which allows for a connection between atomistic and continuum descriptions. A central theme in the Phillips group is the use of methods like those described above to examine nanoscale mechanics in problems ranging from the packing of DNA into viruses to the dissipation in micron sized cantilevers.

Nanomechanics

Tools such as the atomic-force microscope and optical tweezers have made it possible to examine mechanics at the level of individual molecules in the biological setting and at the level of single defects in crystalline materials. Phillips' group aims to construct models of nanomechanical phenomena such as the mechanics of molecules such as DNA and proteins, with emphasis on problems such as the packaging of DNA both in viruses and eucaryotic cells, the mechanics of ion channels and the ways in which proteins unfold in the presence of an applied force. In the context of materials, similar efforts are underway which aim to uncover the relation between dissipation in small scale structures (such as the micron sized cantilevers built and examined in the group of Professor Michael Roukes) and the defects that populate these materials.

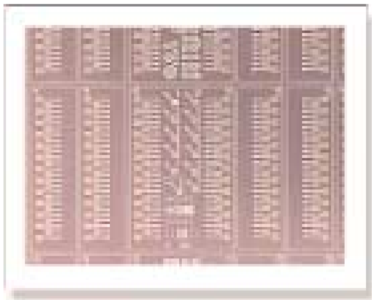
Dynamics of Molecules and Defects

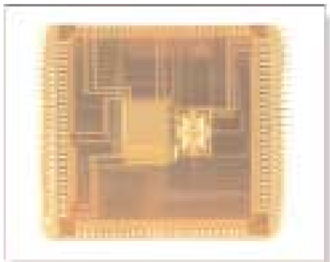
One of the traditional tools for examining the behavior of isolated molecules or individual defects is molecular dynamics in which the trajectories of individual atoms are computed. Work in the Phillips group is aimed at developing alternatives to the full brute force molecular dynamics in which only subsets of the original full set of atomic degrees of freedom are retained. With these methods in hand, the objective is to build higher level models of macromolecular assemblies such as ion channels and molecular motors which will capture the essential features of these systems without having to pay the price of full atomistic simulation. These methods have analogous applications in the setting of more traditional materials where we aim to determine the kinetic properties of defects such as dislocations, cracks and grain boundaries and to build effective equations of motion for such defects which relinquish all further reference to the underlying atomic coordinates.

http://www.me.caltech.edu/faculty/phillips.html

OPTICAL INFORMATION PROCESSING GROUP

DEMETRI PSALTIS





Reconfigurable processors form a new computational paradigm, in which the processor modifies its structure to suit a given application, rather than an application requiring modification to fit a given device. The optically programmable gate array (OPGA), an enhanced version of a conventional FPGA, utilizes a holographic memory accessed by an array of VCSELs (Vertical Cavity Surface Emitting Lasers) to program its logic. Combining spatial and shift multiplexing to store the configuration pages in the memory, the OPGA module is very compact and has an extremely short configuration time, allowing for dynamic reconfiguration. The reconfiguration capability of the OPGA can be applied to solve more efficiently problems in pattern recognition and database searching. Top left, array of VCSELs; right, a complete OPGA chip.

The Caltech research group headed by Professor Demetri Psaltis conducts research in optics, holography, and the application of optical techniques to information systems, including memories, imaging, sensors, and communication. The group has a long-lived interest in and has made significant contributions to the theory of weak holograms and their applications. These include holographic memories and image correlators that have been used in a variety of projects, such as navigation and fingerprint recognition. Involvement in this area generated interest in holographic storage materials, both crystals (mainly lithium niobate) and polymers. It also initiated successful projects in development of components for holographic memories, such as liquid crystal beam deflectors.

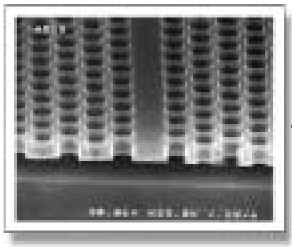
Our group is currently interested in ultra-fast imaging. We are developing fast cameras for nano-sec and femto-sec rates. Changes that occur at these rates are usually very small and thus measured interferometrically. The fact that the cameras under development store frames holographically makes them inherently suitable for this application. Research in this direction also builds on our experience with holographic storage and materials.

Our research focus has also expanded to include strong holograms. These are used to implement novel microscopy techniques that allow imaging in multiple dimensions, optical interconnects, and filters for optical communications. The use of strong holograms for imaging and interconnection applications has sparked interest in the combination of optics and electronics and led to the implementation of an optically programmable gate array (OPGA). It has also generated interest in optics for miniature devices, such as small cameras based on principles of insect vision.

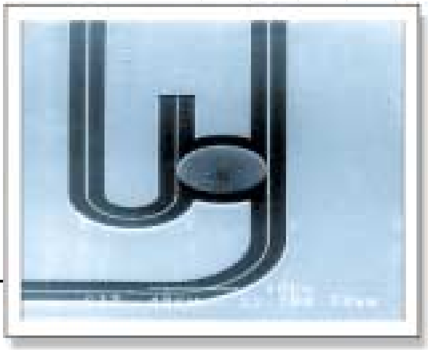
http://optics.caltech.edu/

PHOTONIC CRYSTALS

AXEL SCHERER



Scanning electron micrograph of a photonic crystal waveguide.



High-resolution lithography and high-index contrast waveguides allow us to fabricate compact add/drop filters and switches.

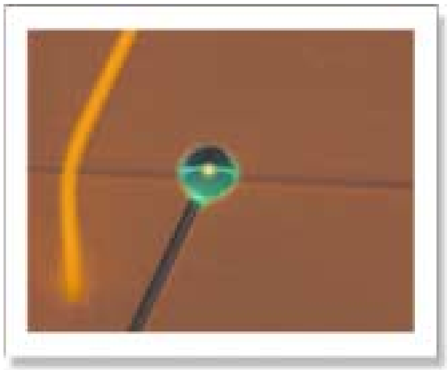
Axel Scherer and his group have developed some of the building blocks which are necessary for defining photonic integrated circuits based on photonic crystals. With these it will be possible to generate, route, filter, or detect light within very small areas on a photonic crystal chip. To demonstrate such photonic integration, the Scherer group is measuring the coupling from waveguides into cavities with geometries such as the one shown in the figure above. Another outcome from work on single-defect photonic crystal cavities is the design of high-Q optical cavities in which the maximum of the optical field lies in an air hole within a photonic crystal. Such cavities, which display Q values in excess of 20,000, are ideally suited to applications in strong coupling experiments, as are required for quantum computation. The group is presently measuring the cold Q values of such cavities in order to evaluate the present limits of realistic manufacturable structures.

The past rapid emergence of optical microcavity devices, such as Vertical Cavity Surface Emitting Lasers (VCSELs) can be largely attributed to the high precision over the layer thickness control available during semiconductor crystal growth. High-reflectivity mirrors can thus be grown with subnanometer accuracy to define high-Q cavities in the vertical dimension. Recently, we have shown that it is possible to microfabricate high-reflectivity mirrors by creating two- and three-dimensional periodic structures. These periodic “photonic crystals” can be designed to open up frequency bands within which the propagation of electromagnetic waves is forbidden, irrespective of the propagation direction in space, and thus define photonic bandgaps. When combined with high-index contrast slabs in which light can be efficiently guided, microfabricated two-dimensional photonic bandgap mirrors provide us with the geometries needed to confine and concentrate light into extremely small volumes and to obtain very high field intensities. Our group is working to use these “artificially” microfabricated cavities in functional nonlinear optical devices, such as lasers, modulators, add/drop filters, polarizers, and detectors.

http://nanofab.caltech.edu/

FIBER-COUPLED MICROSPHERE FILTERS and LASERS

KERRY VAHALA



Micrograph showing a 40-micron diameter silica microsphere that is doped with the rare earth erbium. Upon incorporation into silica, erbium ionizes to the 3+ state and exhibits dipole transitions in the green and near infrared. In the micrograph one of these transitions has been excited by optical pumping through a fiber taper. The taper can be seen in the micrograph as the slightly out-of-focus horizontal line. The green ring emission from the sphere corresponds to a fundamental whispering gallery mode of the sphere. This particular sphere is also lasing in the 1.5 micron band (the important telecom band). The lasing emission is efficiently coupled onto the same fiber taper used for optical pumping.

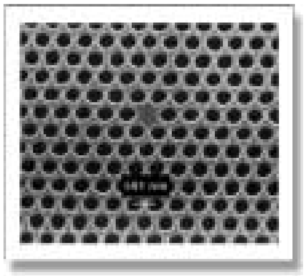
The ability to confine optical radiation in compact resonant structures is of central importance to the construction of optical filters, lasers, and a variety of measurement systems. It is well known that spherical dielectric structures will efficiently confine radiation as so-called “whispering gallery” modes. These modes derive their name from their acoustical analogue (first described by Rayleigh). The resonator Q (storage time normalized by the optical period) provides a convenient measure of confinement time. In wavelength-scale resonator structures, Q values of 1000 are considered excellent. It has been found that dielectric microspheres of silica support whispering gallery modes with Q values as large as 10 billion. Such Q values could prove useful in precision measurement systems and in optical communications. Efficient optical power coupling to these systems is possible using a method pioneered at Caltech in the Vahala group.

In order to confine optical radiation in compact resonant structures, an ordinary optical fiber is prepared having a tapered region by pulling the fiber in flame. The tapered region has a narrow waist (typically a few microns in diameter) permitting access to the electromagnetic field by evanescent coupling in the region around the taper. The taper-to-sphere coupling is extraordinarily efficient with 99.8% optical power transfer possible from the fiber to microsphere resonant modes. It is important to understand that this coupling is completely reversible. In particular, once energy is coupled into the high-spatial-diversity microsphere system, it can be recovered into the single-mode fiber guide with equally high efficiency. As a result, the coupling offers a high-efficiency link between the technologically important single-mode fiber medium and the spatially complex silica microsphere. We have confirmed this in our work on a spheres attached to two fiber tapers. In addition, the high Q of the microsphere modes allows each spatial mode to reside at a precise optical frequency. This provides a convenient “modal address” mechanism based on optical frequency. Overall, these structures provide a possible way of harnessing spatial and spectral attributes of light in a compact and intrinsically fiber-optic compatible package. The highest Q structures are also optically nonlinear at low power (100s of microwatts) so that complex control functions are possible based on the Kerr nonlinearity of silica. Device applications being pursued include a four-port filter that resonantly couples optical power between two fiber cables as well as microsphere lasers. In the latter device, a single optical fiber is used both to convey optical pump power to a microsphere (to create a lasing inversion) and to collect the lasing emission. The figure shows a micrograph of such a microsphere laser. The green equatorial ring is excited state emission associated with the lasing whispering gallery mode. Beyond these device applications, we are also studying the far-reaching implications of coupled-microsphere systems (i.e., photonic molecules) in which resonant power is injected to a multi-sphere system by way of fiber tapers and then allowed to circulate among the coupled modes of the system. The additional degrees of freedom in such a system could one day be used to create compact switching nodes for manipulation of light.

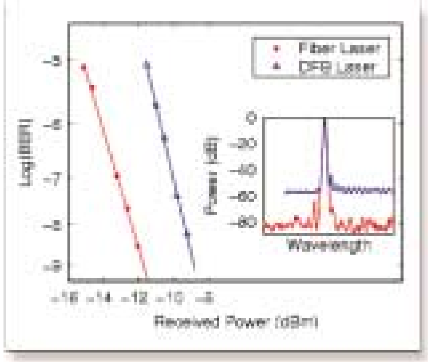
http://www.its.caltech.edu/~vahalagr/

the QUANTUM ELECTRONICS and SOLID STATE LABORATORY

AMNON YARIV



Electron micrograph of a photonic crystal nanocavity laser.



BER performance comparison between the fiber ring laser and a commercial DFB semiconductor laser. The DFB laser requires twice the received power in order to achieve the same bit error rate as the fiber laser. The inset shows the optical spectra, revealing two-orders-of-magnitude better side-mode suppression for the fiber laser.

Professor Amnon Yariv and his research group have pioneered the field of optoelectronics and opened up new fields of study. Distributed feedback (DFB) semiconductor lasers, integrated optoelectronic circuits, optical phase conjugation, external cavity tunable semiconductor lasers, quantum well infrared photodetectors (QWIPs), and all-fiber add/drop filters have all found their beginnings in this research group. Today, advances continue to be made in the research thrusts of analogue and digital signal propagation in fibers, photonic crystal devices, fiber lasers, and sources for wavelength division multiplexing (WDM).

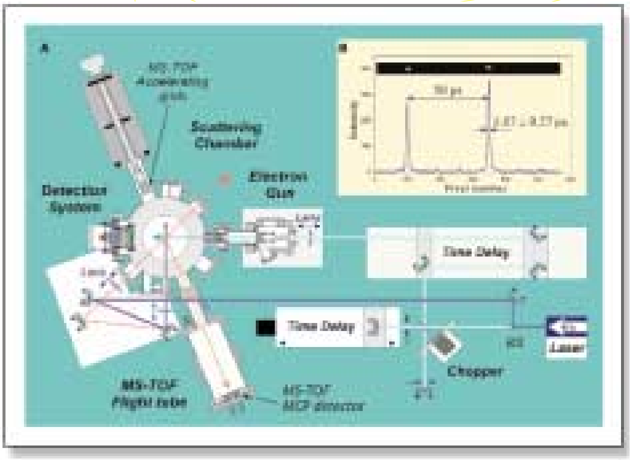
We have studied extensively the physics of semiconductor, distributed feedback (DFB) lasers, including the effects of propagation in optical fiber, using a new measurement technique developed in our group. Bragg gratings and optical fiber have been used to increase and flatten the system response of high-modulation-speed signal propagation, the basis of a new type of transmission system known as dispersion supported transmission (DST). During recent years, polarization mode dispersion (PMD) has become a major limiting factor of optical communication systems. PMD refers to signal distortion due to polarization effects. Our PMD research has resulted in a new theory and novel methods for PMD compensation. We are currently examining possible integrated implementations for a PMD compensator resulting from the new theory. We have recently developed a new pulse measurement setup based on time-resolved optical gating and dispersive propagation (DP-TROG), enabling us to characterize a pulse completely in amplitude and phase from monolithic mode-locked lasers designed and fabricated by our group. We have proposed a new method for super-high-speed A/D conversion (>20 Gbit/sec) based on a combination of semiconductor mode-locking techniques and wavelength division multiplexing (WDM) which exceeds the maximum conversion rate of current state-of-the-art electronics. We have also developed a novel fiber ring laser. The laser has orders-of-magnitude better frequency stability and noise performance than semiconductor DFB lasers. It handily outperforms a semiconductor DFB laser in digital transmission tests, even at 10 Gbit/sec. This laser is now developed commercially for the DWDM market by Orbits Lightwave, Inc., a Caltech-based start up. Our group has a large, ongoing effort in the field of optical microstructures, including photonic crystal-based devices, microresonators, and modulators. In 1999, we successfully demonstrated for the first time lasing in thin-film photonic bandgap-based microcavities. Lasing from a single photonic lattice point defect was shown—possibly the smallest modal volume semiconductor laser ever demonstrated. Multiple microcavities can be coupled together to form a coupled resonator optical waveguide. For a given optical power input this is expected to enhance the optical intensity by a factor of hundreds or even thousands, increasing the efficiency of nonlinear optical processes. Coupling optical waveguides to resonators makes possible the ability to improve performance of modulators and switches by orders of magnitude. Using the concept of critical coupling, we have designed a modulator with sub-1-volt half-wave modulation voltage. We are currently exploring implementations in semiconductors and electro-optic polymers.

http://www.its.caltech.edu/~aphyariv/

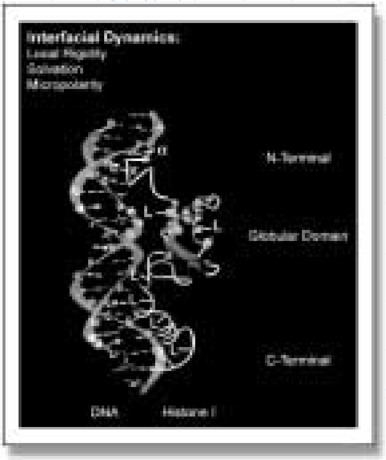
a REVOLUTION in MOLECULAR SCIENCES

AHMED ZEWAIL

Newly designed electron diffraction machine for time-resolved structural changes.



The field of molecular sciences is witnessing a revolution. From elementary reaction dynamics to protein folding, new physical tools are being exploited to study molecular structure and dynamics in chemistry and biology. The great strides made in both spatial and temporal resolution, down to the atomic scale, provide new opportunities to elucidate the nature of elementary processes in complex molecular systems and to relate dynamics and structures to function in real systems at the most fundamental level. To address the complexity of real systems, it is essential to draw upon different scientific sub-disciplines and to exploit synergies between them. Professor Zewail and his group are at the leading edge of such investigations.



A typical protein DNA system for studies of molecular recognition under physiological conditions.

The goal of the Laboratory for Molecular Sciences (LMS) is to conduct multidisciplinary research on fundamental processes in complex molecular systems with atomic resolution. Collaborations have been established to pursue this objective in a wide range of complex systems using experimental, theoretical, and computational approaches. These efforts draw upon the active participation of research groups from biological, electrochemical, organic, inorganic, and chemical physics disciplines. Our laboratory is equipped with state-of-the-art resources for ultrafast studies, including lasers, x-ray diffraction, electron diffraction, high-speed computing, and electrochemistry. The activities encompass six major areas, including: solvation and weak interactions, excited-state dynamics, electrocatalysts and interfaces, time-resolved studies of biological systems, neuronal receptor proteins, and electron and energy transfer in molecular assemblies.

http://www.its.caltech.edu/~femto/