2010 MRS Spring Meeting Reveals Integration of Various Materials Developments

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With 42 symposia highlighting energy, functional materials, nanomaterials, and soft materials, the **2010 Materials Research Society Spring Meeting**, held in San Francisco on April 5–9, drew over 4500 attendees from around the world. Meeting Chairs **Anne C. Dillon** (National Renewable Energy Laboratory), **Robin Grimes** (Imperial College London), **Paul McIntyre** (Stanford University), and **Darrin J. Pochan** (University of Delaware) also provided tutorials as well as professional development opportunities, an equipment exhibit of over 120 exhibitors, seminars on U.S. government funding for materials research, and the inaugural Innovation Forum that brought together researchers with industry leaders and venture capitalists. The Meeting featured plenary speaker Siegfried Hecker of Stanford University and honored MRS award recipients Warren C. Oliver of Nanomechanics, Inc. in Oak Ridge, Tenn. and George M. Pharr of University of Tennessee/Oak Ridge National Laboratory for their joint inaugural Innovation in Materials Characterization Award as well as Mark C. Hersam of Northwestern University for Outstanding Young Investigator. Also, the Kavli Lectureship was presented to Harry Atwater of the California Institute of Technology.

Energy

Energy systems analyst Paul Denholm of the National Renewable Energy Laboratory opened his Symposium X presentation with the question of whether wind and solar energy can be major contributors to a reliable energy system. The U.S. electric grid, as dominated by fossil fuels, is very reliable and low cost. Extensive analysis, he said, has demonstrated the feasibility of deriving up to 20% of the country's electricity from wind and solar with little cost penalty, significant emissions reductions, and no impact on reliability. These sources would replace some of the energy derived from nonrenewable sources. More recent studies have demonstrated technical feasibility of up to 30% dependency on renewable energy sources. Unfortunately, the scenario of deriving more than 30% energy from wind and/or solar has not yet been explored in detail, as it appears that the benefits of renewable energy begin to decrease due to limited correlation of supply and demand. In Texas, for example, electricity is sold at very low cost to utilities during low demand periods since it otherwise would need to be thrown away since certain power plants cannot be completely turned off. One solution, Denholm said, would be to make the system much more flexible than it is currently. In addition, enabling technologies may be required. Storage may be an important option, but is one of many options to increase the utilization of renewable electricity sources.

In addition to the systems challenges discussed by Denholm, during the Kavli presentation Harry Atwater of the California Institute of Technology made the argument that solar energy is the best candidate to meet global energy requirements in the future. In his Kavli Lecture on nanoscience, Atwater represented a connection between nanophotonic structures and photovoltaics. The available useful energy from the sun is 1000 TW, he said, which is significantly larger than the energy available using other technologies such as hydro, wind, and geothermal. However, that sunlight needs to be channeled and collected efficiently. Atwater's group has been able to form large areas of Si wire solar cell arrays, establishing complete control over the periodicity and regularity of the arrays. In addition, by using a polymer, very flexible, large-area arrays of wires can be formed. With the addition of scattering nanoparticles, high absorption can be achieved. These hyper light-trapping wire array cells represent a new paradigm for flexible thin-film crystalline Si photovoltaics, he said. Cell efficiencies of ~14% in dense wire arrays are realistically possible. Also 20× optical concentration in sparse wire arrays is feasible. For an equivalent volume of Si, wire arrays can exceed the planar light-trapping absorption limit particularly at infrared frequencies, Atwater said. The Fred Kavli Distinguished Lectureship in Nanoscience is given by the Kavli Foundation.

Speakers in several symposia reported on their research in the area of photovoltaics (PV). Because defects in photovoltaic materials play a key role in determining materials properties critical to PV applications, improved understanding and control of defects may enable the discovery of new classes of photovoltaic materials, paving the way for future generations of

The 2010 MRS Spring Meeting Exhibit featured 120 international exhibitors who displayed a full spectrum of equipment, instrumentation, software, publications, and services for the materials research community.

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

solar cells. In this spirit, J. Ager (Lawrence Berkeley Natl. Lab.) opened Symposium EE by discussing the role of defects in shaping three new and emerging PV materials. Control of native defects and careful thermopower measurements reveal that Mg doping produces *p*-type InN, opening up the full InGaN bandgap tuning range for PV applications. Control of vacancies in ferroelectric $BiFeO_3$ led to *p*-type conductivity and a Schottky-type solar cell. Ager also reported that alloying AlN with ZnO in thin films produced visible absorption, suggesting that mixed non-isovalent alloys may be good light absorbers for PV applications.

K. Leo (TU Dresden) announced, in Symposium HH, a new record efficiency for a tandem organic PV device of 7.7%, in a device fabricated at the company Heliatek. This device, made using the thermally evaporated small molecule approach, has an area of 1.1 cm^2. The result was certified at Fraunhofer ISE in Germany. Initial lifetime testing of the device is very promising with projections of well beyond 10 years, Leo said.

In Symposium DD on thermoelectric materials, D.G. Cahill (Univ. of Illinois, Urbana-Champaign) said a way to improve efficiency of thermoelectric materials often involves the introduction of nanostructures to reduce the thermal conductivity of the lattice. Nanostructures are intended to scatter the relatively long-wavelength acoustic phonons that carry a significant fraction of heat in semiconductor alloys. He reported on work in collaboration with colleagues at the University of Oregon, Lincoln Laboratories, University of California (UC) Santa Cruz, UC-Berkeley, and UC-Santa Barbara to investigate the thermal conductivity of a wide variety of nanostructured thermoelectric materials by time-domain thermoreflectance (TDTR). The research team found that ErAs nanodots lower the thermal conductivity of InGaAs and reduce the TDTR frequency dependence. Nanodots in InGaAs are effective in scattering phonons with mean-free-paths in the range of hundreds of nanometers. PbSe nanodots are not as effective in lowering the thermal conductivity of PbTe; essentially the same thermal conductivity is observed in alloys with the same average composition. The lattice thermal conductivity of PbTe/PbSe nanodots superlattices does not fall significantly below 1 W/m K. This can be understood, Cahill said, based on the small acoustic mismatch between PbTe and PbSe and the strong anharmonicity of PbTe. While nanostructures can reduce thermal conductivity in thermoelectrics, they appear to have a greater effect on materials with high thermal conductivity to start, rather than further helping preferred materials that have lower thermal conductivity to start.

In the area of solid-state batteries (Symposium CC), R. Kanno (Tokyo Inst. of Technology, Japan) gave a review on the current status of solid-state inorganic electrolytes which are critical components for the successful development of solid-state Li-ion batteries. To take advantages of an "all-solid" and safer form of the battery, Kanno proposed to develop the batteries using sulfur as the electrode material with a new electrode structure. The two- or three-dimensional electrode structure

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https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

◂ **George M. Pharr** (left) of University of Tennessee/Oak Ridge National Laboratory and **Warren C. Oliver** of Nanomechanics, Inc. in Oak Ridge, Tenn. delivered the talk on their joint work recognized by the inaugural MRS Innovation in Materials Characterization Award, endowed by Gwo-Ching Wang and Toh-Ming Lu of Rensselaer Polytechnic Institute.

Mark C. Hersam (left) of Northwestern University receives the MRS award for Outstanding Young Investigator from MRS President **David S. Ginley** of the National Renewable Energy Laboratory. ▾

▴ **Siegfried Hecker** of Stanford University delivers the plenary address at the 2010 MRS Spring Meeting.

Following the presentation ▸ of his Kavli lecture, **Harry Atwater** of the California Institute of Technology (left) converses with a Meeting attendee.

seems to be a new approach for all solid-state cells to reduce interfacial resistance and to improve the utilization of active materials. These new electrodes are applied to the all solid-state battery, and the reaction mechanism is being studied based on the electrode structure analysis using small- and wide-angle diffraction measurements.

Other areas covered in energy included nanoscale charge transport in excitonic solar cells, computational approaches to materials for energy, polymer materials and membranes for energy devices, actinides, nuclear waste management, and materials for nuclear applications and extreme environments.

In the plenary presentation on nuclear energy, Siegfried Hecker, professor and co-director of the Center for International Security and Cooperation (CISAC) at Stanford University, addressed the intersection between science and policy in the nuclear arena. "Nuclear energy can electrify the world, and can also destroy it," he said. If we are to see a renaissance in nuclear power, it is likely that most nuclear power expansion will be in developing countries such as China or India, since they need electricity. Hecker described the nuclear fuel cycle and the paths that could lead to weapons grade plutonium or uranium. To avoid increasing the risk of nuclear proliferation as nuclear power spreads to the developing world, it will be crucial to develop technical, institutional, and political barriers. With or without a nuclear renaissance, Hecker said that the greatest concern is not a nuclear-armed government, but rather nuclear materials falling into the hands of terrorists. According to Hecker, the greatest risk of such threats are Pakistan, highly enriched uranium research reactors, the Russian nuclear complex, North Korea, Iran, and Kazakhstan (the former Soviet nuclear testing ground). In recounting his own experience in working global nuclear threats, Hecker emphasized the importance of the people dimension of the problem—he has found it important to understand people, their cultures and their histories.

Functional Materials

T.N. Theis from IBM Research asked the question that has been making materials researchers uncomfortable for the past few years—how to scale the unscalable? As an industry insider, Theis explained the "real" challenge rests in using emerging materials for silicon integration. In a presentation in Symposium J, he explained how the subthreshold slope of a field-effect transistor (FET), which effectively determines how fast a chip will be heated

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

up, can be reduced by using alternative architectures such as tunnel FETs that cut off the high energy tail of the Boltzmann distribution, ferroelectric gates that offer a negative gate capacitance which allow small gate voltage swings, and spin-FETs that transduce a voltage to a spin state which is gated and subsequently transduced back to a voltage. All of these effectively reduce the subthreshold slope of the FET. Many groups have fabricated prototypes of tunnel FETs, while the latter two are still in the state of conceptual design, Theis said. Theis showed new materials such as silicon nanowires and graphene that could be used to implement these new device concepts.

One of the major obstacles to the realization of a multilevel storage technology based on phase-change materials is drift. Though observations of this drift phenomenon have been reported already in various materials and device geometries, no clear explanation for the effect has been achieved thus far. However, in Symposium H, R. Agarwal (Univ. Pennsylvania) provided compelling experimental evidence for one of the explanations for this drift. Agarwal showed that stress relaxation in the amorphous phase is the source for the drift. In his group, $Ge_2Sb_2Te_5$ nanowires have been produced and tested electrically. Agarwal found drift exponents in the amorphized nanowires, which are extremely low in comparison with values reported in previous studies. His group embedded the nanowires under a dielectric film, introducing mechanical stress to the phase-change material. When it was amorphized, it led to an increase of the drift exponent to values comparable to previous studies.

Besides some general considerations on physical models for the description of phase-change–based memory devices, I. Karpov (Intel) discussed in his talk (in a joint session of Symposia G and H) the properties of a stackable cross point phase-change memory. In this cell geometry, besides the common phase-change material that performs memory switching between its amorphous and crystalline phase (PCM), another chalcogenide is introduced as a purely electronic switch on top of the memory-cell. This second so-called Ovonic threshold switch (OTS), with a threshold voltage well below the one of the PCM, serves as selector in the cross point structure that is necessary to prevent parasitic currents and concentrate any action on the chosen cell. This cross point topology promises to provide an ideal scaling path for $4F^2$ implementation, Karpov said.

Defects in crystals are not limited to grown-in defects. Materials processing for device fabrication is very complex. Ion implantation in particular is troublesome as it creates damage in the crystals due to annealing at temperatures in excess of 1600°C. Some issues with this high temperature anneal was described by H. Tsuchida (CRIEPI) in Symposium B. He showed that basal plane dislocations (BPDs) were generated in the epitaxial layer during the anneal process. BPDs are particularly troublesome in SiC bipolar devices because they are known to form stacking faults when in operation.

D.A. Schoner (Acreo AB) presented some novel solutions to the ion implantation issue. He showed how many devices can be manufactured with just the combination of different epitaxial layers and trench etching. These devices were manufactured and performed well without ion implantation. This has the potential of reducing process steps, reducing cost of device manufacturing, and reducing dissociation formation.

Highlighting the capability of showing new applications of traditional materials or techniques were Warren C. Oliver (Nanomechanics, Inc.) and George M. Pharr (University of Tennessee/Oak Ridge National Laboratory) as they discussed their work in nanoindentation. Oliver and Pharr received the inaugural MRS Innovation in Materials Characterization Award (IMC), endowed by Gwo-Ching Wang and Toh-Ming Lu of Rensselaer Polytechnic Institute. Since Oliver and Pharr introduced their nanoindentation technique for characterizing mechanical properties of materials in 1992 (published in the *Journal of Materials Research* and receiving over 5,400 citations so far), measuring hardness and elastic modulus by nanoindentation has been widely adopted and employed for the characterization of mechanical behavior at small scales. Since its original development, the method has undergone numerous refinements and changes brought about by improvements to testing equipment and techniques, as well as advances in the understanding of the mechanics of elastic-plastic contact. The method now forms the basis of an international standard for load and depth-sensing indentation testing.

Oliver and Pharr said that in the early years, the obvious applications for the method were in the measurement of hardness and modulus of thin-film materials used in the semiconductor, magnetic storage, and optical coatings industries, as well as materials with hard coatings that improve wear resistance and tribological performance. However, over the years, the utilization of the method expanded to include a much broader range of materials and scientific disciplines, several of which they never envisioned when developing the technique.

In one example, long-term radiation damage was investigated in a 570-million-year-old zircon rock with radioactive elements. The radiation induced amorphous areas. Nanoindentation was used to measure hardness as a function of position and dose, and hardness tracked the long-term dose in a remarkable manner, they said. The damage was similar to that in short-term irradiation.

Another application in the biomedical arena is to characterize mechanical properties of atherosclerotic plaques in arteries for use in computational models that can be used in the diagnosis and treatment of atherosclerosis.

More recently, some very unusual applications of nanoindentation have come to light. In one example, a volcano erupted in the Laacher See region (in present-day Germany) around 11,000 BC and the local population disappeared from the region for several hundred years. It was hypothesized that animals ate plants covered with abrasive ash that destroyed their teeth, and died out, causing the human migration. Nanoindentation of teeth from that time period and ash revealed that indeed the ash particles were significantly harder than the teeth and thus capable of producing severe abrasion.

Oliver and Pharr also described a recent article on the characterization on low-*k* dielectric materials that made extensive use of nanoindentation characterization techniques. The article was co-authored by Wang and Lu who endowed the IMC award.

Other areas covered in functional materials included amorphous and polycrystalline thin-film silicon, inorganic and hybrid materials for electronics and photonics, perovskite surfaces and interfaces, plasmonic materials and metamaterials, chemical–mechanical planarization as a semiconductor technology enabler, advanced interconnects for micro- and nanoelectronics, nonvolatile memories, high-temperature superconductivity, and materials for end-of-roadmap scaling of complementary metal oxide semiconductor devices.

Nanomaterials

"Graphene is the strongest material ever measured, and may be the strongest ever to be measured," said James Hone from Columbia University, presenting nanoindentation measurements of these single layers of carbon with an ultimate strength

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

of 130 GPa. Early measurements led to broken atomic force microscopy tips because the silicon tips failed before the graphene. Now diamond tips are used. Furthermore, Hone showed in Symposium S that graphene stretches, obtaining ultimate strains of over 25%. This interesting combination makes it possible to probe mechanical properties deep into the nonlinear elastic regime. In fact, Hone said, this nonlinear stretchiness needs to be considered to understand graphene. The ultimate strength was determined by including a quadratic term to make a nonlinear parabolic curve, reducing the strength from the unrealistic value of 200 GPa that first fell out of the measurements. The mechanical properties were tested on circular membranes of graphene placed over a hole in a silicon substrate. Finite element modeling shows that the van der Waals forces are enough to hold the material together. Hone also tested variations of graphene. Hydrogenated graphene is softer, yet annealing shows this is reversible, with graphene's elastic modulus and strength returning. Furthermore, Hone's group measured frictional behavior of graphene and other 2D materials of MoS_2, $NbSe_2$, and nano-BN. These materials show an unexpectedly strong dependence of the frictional force on the number of atomic layers, with thinner samples demonstrating higher friction by factors of as much as three times compared to the bulk. This demonstrated that the friction force was due to something other than the intrinsic properties of the materials, Hone said. By studying friction of these materials on various substrates, Hone's group found that the friction is controlled by how tightly bound the top layer is to the layers or substrate below. This work, done in collaboration with colleagues at the University of Pennsylvania, showed that deformation builds up at the leading edge of the friction probe in the more loosely bound layers, causing resistance and thus a higher friction measurement.

Recently, significant progress has been made in both *in situ* and *ex situ* small-scale mechanical testing methods, which have greatly improved the understanding of mechanical size effects in volumes from a few nanometers to a few microns. This field has progressed from nanoindentation in 2000 to nanocompression testing in 2006 to the current nanoscale tensile testing in 2009 and later. Studies on nanoscale pillars formed using focused ion beams have been subjected to compression tests, and it has been shown that smaller is indeed stronger. However, these tests on micropillars have not yet demonstrated the theoretical strength of the materials. In his talk in Symposium V, A. Minor (UC-Berkeley) described the use of an *in situ* tensile testing setup in a transmission electron microscope used to test copper specimens. In the tensile tests, dislocation activity was observed through the whole gauge section, with no strain localization. The strength could be correlated to defects and the evolution of dislocation density could be plotted as a function of strength. The tensile testing allowed for homogeneous deformation so that exhaustion of defects led to increasingly higher strengths. Minor discussed the effects of *in situ* annealing on the strength of Mo nanopillars. In fact, Minor said, after the annealing, the pillars reached the fundamental upper limit of strength. Thus, the *in situ* nanomechanical testing could be mapped to strength behavior, Minor said.

M. Bjoerk presented results of IBM Zurich's ongoing efforts to fabricate nanowire-based reliable tunnel field-effect transistors (TFETs) that can achieve a subthreshold slope of 60 mV/decade, the current limit in planar silicon metal oxide semiconductor field-effect transistors. Bjoerk explained, in Symposium P, the details of their silicon nanowire growth by chemical vapor deposition, and *in situ* doping with phosphorus and boron. A modulation-doped silicon nanowire serves as the channel of a TFET. The research team observed a significant change in the nanowire morphology with boron doping, that is, the nanowires

Poster Prizes Awarded at 2010 MRS Spring Meeting

The 2010 Spring Meeting Chairs awarded prizes for the following best poster presentations: (M3.11) **Metallic or Insulating Interfaces in Epitaxial $SrTiO_3$/RO (R = La, Pr, Nd, Sm, Y) Monolayer/$SrTiO_3$ Heterostructures**, H.W. Jang (University of Wisconsin, Madison; Korea Institute of Science and Technology), D.A. Felker, C.M. Folkman, C.-W. Bark, S.-H. Baek, S. Lee, M.S. Rzchowski, and C.-B. Eom (University of Wisconsin, Madison), K. Janicka and E.Y. Tsymbal (University of Nebraska), C.T. Nelson, Z. Yi, and X. Pan (University of Michigan, Ann Arbor), and Y. Zhu (Brookhaven National Laboratory); (P13.51) **Dislocation-Driven Growth of ZnO Nanowires**, S.A. Morin, J. Tong, and S. Jin (University of Wisconsin) and M.J. Bierman (California Institute of Technology); (T10.49) **Anisotropic Type II Nanocrystal Heterostructures**, H. McDaniel and M. Shim (University of Illinois, Urbana-Champaign); (LL3.15) **Sub-Micron Patterning of Colloidal Particles by Confinement of Drying Solutions in Wrinkles**, A. Schweikart, M. Tebbe, A. Fortini, A. Wittemann, M. Schmidt, and A. Fery (University of Bayreuth, Germany); (LL9.6) **STM Study on Binary Molecular Assemblies on Au(111)**, Y. Wakayama (National Institute for Materials Science, Japan); (OO3.2) **The Morphology of Integrated Self-Assembled Monolayers and Their Impact on Devices—A Computational and Experimental Approach**, M. Novak, C. Jaeger, T. Clark, and M. Halik (University Erlangen-Nürnberg, Germany); and (PP9.32) **Biomimetic Metallic Electrodes for Intracellular Electrical Measurements**, P. Verma, W. Cai, and N. Melosh, (Stanford University).

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became highly tapered. However, the researchers did not observe such changes in the phosphorus-doped nanowires and went to further characterize them electrically. They found out that beyond a doping of 1.5×10^{20} cm^{-3} the resistivity of the doped nanowires did not decrease anymore, demonstrating a saturation in phosphorus incorporation into the nanowires. By measuring the current–voltage characteristics of nanowires of different diameters and at different temperatures, they verified a recently proposed theory that the activation energy of dopants inside a nanowire is higher than that in a bulk semiconductor. Bjoerk's group also fabricated TFETs based on these nanowires. However, they are yet to surpass the lower limit of the subthreshold slope just mentioned.

In Symposium Q, S.T. Lee (City Univ. of Hong Kong) addressed the area of Si nanowires obtained by metal-assisted etching of Si wafers. Lee said that such a simple technique can result in highly oriented straight or kinked Si nanowires and single-crystalline porous Si nanowires as well as ordered microporous Si films. This method is now being widely used in various groups for the study of applications in photovoltaics, photoelectrochemical cells, Li-ion batteries, and thermoelectric materials.

Appraising the current need for controlling shape, composition, and doping of metal oxides, G. Westin (Uppsala Univ.) explained, in Symposium N, solution-based aloxides can be used to dope materials like Co-ZnO and WO_3-TiO_2 that are finding their eventual applications in photovoltaics. He also described a new synthesis process to demonstrate metal in ceramic nano inclusion materials, which allows for synthesis of thin films and high surface area powders.

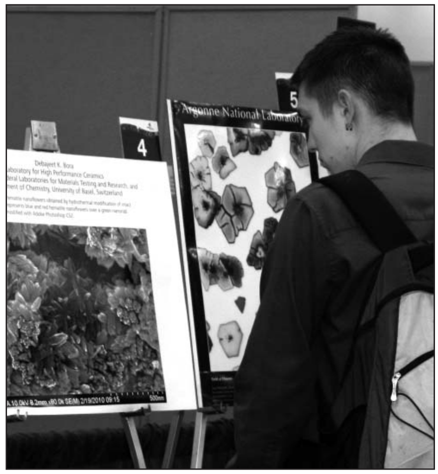
Other topics covered in nanomaterials included multifunctional nanoparticle systems, photovoltaic and optoelectronics from nanoparticles, carbon nanotubes, and scanning probe microscopy used in the frontiers of nanobio-science.

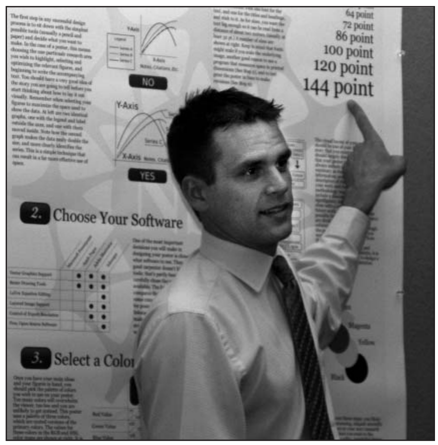
Soft/Biomaterials

In nervous systems in all animals, neurons play a crucial role in memory and learning. A typical neuron has a long arm, called an axon, that contacts another neuron to form a synapse. Synaptic vesicles containing neurotransmitters are clustered at the synapse. In response to an action potential, neurotransmitters are released across the synapse. The more a synapse is used, the higher is the vesicle clustering, and the higher is the neurotransmission efficiency. The synapse thus "remembers" its usage in the near past, and modifies its neurotransmission efficiency accordingly. In his presentation in Symposium QQ, T. Saif (Univ. of Illinois, Urbana-Champaign) described the role that mechanical tension in the axon plays in synaptic function.

In vivo experiments were conducted on the embryonic *Drosophila* (fruit fly) nervous system using a novel biomicroelectromechanical system force sensor. It was observed that mechanical tension is required in the axons for vesicle clustering at the neuromuscular presynaptic terminal; thus tension is required for normal synaptic function. When the tension was removed, such as by slicing the axon with a laser, the clustering disappeared, but it reappeared with the application of tension. In fact, the *in vivo* axons were found to maintain a rest tension of about 1–2 nN. An increase in mechanical tension resulted in an increase in clustering. The axons are mechanically robust against very large (more than 100%) stretching. Under sudden stretching, the axonal force increased momentarily, but the force relaxed over time if the stretch was held. If the stretched axon is suddenly released, it shows an elastic recovery followed by an active shrinking when it builds the rest tension again. This restoration is maintained even after large stretches. Preliminary observations suggest that axons may grow under large stretches, and undo the growth upon release of stretching, to regain the rest tension. Saif's group has developed a model to explain these observations based upon the behavior of F-actin. When there is a force, the actin forms a network in the synaptic junction along with vesicles. When the force is removed, the actin depolymerizes and vesicle clustering cannot occur. There is thus the interplay between tension, the F-actin network, and vesicle clustering. Mechanical force/tension is thus important for synaptic function. Saif closed by posing the provocative question, "Is memory fundamentally linked to mechanical tension in axons?"

Also in Symposium QQ, M. Dao of S. Suresh's group at the Massachusetts Institute of Technology gave an overview of research uncovering the profound effect that diseases such as malaria can have on mechanobiological characteristics of human cells such as red blood cells (RBC). The RBC is a simple model cell without a nucleus; it typically undergoes severe and large reversible elastic deformation as it makes its way through the human body, which is crucial since it has to traverse some very narrow openings. When the





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body is infected with malaria, the RBCs lose this deformability and they also show increased adhesion to the endothelium. Several methods have been developed to measure the elastic properties of RBCs such as using optical tweezers. Dao presented some of these results, clearly demonstrating deleterious measurable effects on the elastic modulus of an RBC in different stages of malaria caused by *Plasmodium falciparum*. One aspect ignored by previous researchers was the temperature, with tests conducted at room temperature; however, Suresh's group has performed measurements at human body temperature and fever temperature (37°C and 41°C, respectively) and have shown that temperature has a further deleterious effect. The exception is when the RESA protein is removed. However, even then, in the advanced malarial trophozoite stage, the elastic modulus significantly increases, demonstrating stiffness.

Dao also gave an overview of some studies done recently involving the human spleen, which in one sense acts as a filter. Dao said that 90% of blood circulating through the spleen is closed; however, the remaining 10% is subject to open circulation with blood exiting the system but re-entering through inter-endothelial slits in the *splenic sinus*. One of the functions of the spleen is to filter out any RBCs with parasites. The researchers were able to model this process and correlate this with the elastic properties of the RBCs. These studies represent an important body of work at the interface between biology and materials science, which have major implications for future disease diagnosis and therapeutics, said Dao.

T. Knowles (Univ. Cambridge) gave a brief explanation, in Symposium QQ, on how mechanical properties of protein-based biomaterials can be used to give insight into protein-protein interactions. Knowles shared his findings about the hierarchical assembly of amyloid fibrils that can then be cast into films. The films are as strong as bone, and show remarkable stiffness second only to materials like carbon nanotubes. Clearly having an advantage in terms of making macroscopic films, amyloid biofilms signify an important discovery in the field, said Knowles.

R. Larson (Univ. Michigan) described a unique analysis into the evaporation of water drops on surfaces and the assembly of particles post-evaporation. In Symposium MM, citing previous work in the field, Larson explained the key factors which alter assembly patterns of particles post-evaporation of water droplets, including salt concentration and addition of ethanol. Furthermore, he showed a series of interesting "soccer ball" patterns obtained after evaporation of bovine serum albumin and Na salts containing water droplets. He concluded by underscoring some important mechanisms, namely, nucleation, diffusion, contact line pinning and depinning, for evaporative self-assembly of proteins using water droplets.

Layer-by-layer (LbL) self-assembly is well known for its versatility for making nanometer thin films over planar surfaces that can have varying pH and salt concentration, can incorporate nanoparticles, and now can be formed through a variety of

Graduate Students Receive Gold and Silver Awards

Graduate Student Awards were announced during an evening ceremony on April 7 at the 2010 Materials Research Society Spring Meeting in San Francisco.

Gold Graduate Student Awards were awarded to (*left to right*): **Jia Zhu** (Stanford University), **Jason Valentine** (University of California, Berkeley), **Bharat Jalan** (University of California, Santa Barbara), **Vincent Holmberg** (University of Texas, Austin), **Morgan Putnam** (California Institute of Technology), **James Rondinelli** (University of California, Santa Barbara), and **Dominic Lencer** (RWTH Aachen University). Not shown is **Brian Hardin** (Stanford University).

Silver Graduate Student Awards were awarded to (*front row, left to right*): **Hanying Li** (Cornell University), **Laura Cote** (Northwestern University), **Claire Cobley** (Washington University), **Bianca Haberl** (Australian National University), and **Ho Cheung Shum** (Harvard University); and (back row, left to right): **Jun Wang** (Iowa State University), **Xinran Wang** (Stanford University), **Yanguang Li** (Ohio State University), **Yongye Liang** (University of Chicago), **Tejinder Singh** (University of Massachusetts, Amherst), **Noy Bassik** (Johns Hopkins University), **Jeffrey Kuna** (Massachusetts Institute of Technology), **Kamal Asadi** (University of Groningen), and **Vivek Kalihari** (University of Minnesota).

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

coating application methodologies. Introducing spin coating as a new technique for LbL, V. Tsukruk (Georgia Tech), in Symposium MM, compared the technique to conventional LbL and demonstrated the ability to obtain two to three times thicker coatings; however, process times are significantly reduced. Detailed studies with neutron reflectivity also showed that the layers become more stratified and there is less intercalation between layers as in conventional LbL. Spin coating which leads to fast solvent removal and a strong shear flow thus helps better engineer coatings, Tsukruk said.

In Symposium OO, speakers showed that the self-assembly of colloidal particles is moving beyond the self-assembly of simple spheres, to the realm of anisotropic particles with a variety of surface chemistries that allow programmable binding interactions. T.G. Mason (UC-Los Angeles) reported on the depletion attraction-mediated self-assembly of lithographic particles with potentially arbitrary shapes and showed that the attraction between different surfaces of lithographic particles can be varied by changing the roughness of their surfaces. Two surfaces with randomly distributed asperities will only be attractive if the size of the depletion agent (a solution of particles much smaller than the lithographic particles) is larger than the height of the asperities. Thus, by using faces with differently sized asperities, and gradually increasing the size of the depletion agent, different pairs of faces can be rendered attractive in a defined sequence. Mason said this can allow the hierarchical assembly of particles in at least five stages.

The technology of electronic systems which can arbitrarily deform over objects of complex shape or comply with the softness and mobility of biological tissues is rapidly developing. Such systems have the ability to stretch and contract, and simultaneously can provide reliable electrical functionality. Symposium JJ provided a forum to highlight the latest advances as stretchable electronics push past the boundaries of the past goals of macroelectronics (i.e., large area, static displays), instead striving for rugged electronic appliances which can be rolled, stretched, and conformed to any 3D surfaces. T. Someya (Univ. of Tokyo) presented results on organic field-effect transistors (OFET) which could be driven at low voltages (2 V). These devices remained operational when bent to minute radius (R_{min} ~ 150 μm) and kept in air for up to 100 days. A ring oscillator was capable of 30 Hz operation at 2 V whose performance was not degraded by mechanical deformation, representing the fastest stretchable OFET circuit to date. Another strategy for fabricating conformal, high-performance circuits is by direct transfer to complex 3D shapes. X. Xu (Universal Display Corp.) presented work in collaboration with S. Forrest's group (Univ. Michigan) on a 100 × 100 organic photodetector fabricated on a 1 cm radius hemisphere. By using a technique they call cold-welding, the photodetector array was patterned directly on the hemisphere with micron resolution. With a 20 ns impulse response, the array is suitable for video-rate imaging.

M. Yamato from the Tokyo Women's Medical University introduced a strategy for regenerative medicine to recover tissue functions. The method uses a temperature-responsive cell culture surface consisting of a temperature-responsive polymer covalently grafted by electron beam irradiation or other chemical reaction. Cells are cultured on a surface grafted with poly(*N*-isopropylacrylamide). The polymer changes from hydrophobic to hydrophilic as the temperature is reduced below 32°F. The water held by the polymer in the hydrophilic state expands the polymer surface, and pushes the cell sheet away from the substrate. Then all of the cells are harvested from the dish as a single contiguous cell sheet. Since these cell sheets retain the extracellular matrix deposited during culture below them, integration to tissue or other cell sheets is observed immediately after the transplantation, Yamato said in a presentation in Symposium PP. These surfaces achieve temperature-responsive cell adhesion and detachment with no need for a proteolytic enzyme such as trypsin or dispase used in more conventional treatments using biodegradable polymer scaffolds.

In this study, Yamato showed the application of these transplantable cell sheets to treat corneal defects, as well as other ailments. If only one eye is affected, cells from the other eye are used. When both eyes are affected, the patients' own oral mucosal epithelial cells are used as the cell source. This work has reached the stage of clinical trial under the European Medicines Agency, with approval anticipated in 2011. It has further received the "stamp" of approval of sorts by having a postage stamp in Japan depicting this work.

Other topics covered in soft/biomaterials included charge transport in organic electronics, micro- and nanofluidics systems, and biomimetic and hybrid materials.

Hersam Addresses Nanoelectronic Materials in Award Talk

Mark C. Hersam of Northwestern University, who received the 2010 MRS Outstanding Young Investigator award, said that relatively simple chemistry can add significant value to carbon-based nanoelectronic materials and devices, and monodispersity in structure and surface chemistry enables improved properties in a diverse range of applications. He said that current synthetic methods yield polydisperse mixtures of carbon nanotubes (CNTs), and post-synthetic methods for sorting by diameter, electronic type, chiral handedness, and number of walls are highly desirable.

Using surfactant chemistry and density gradient ultracentrifugation (DGU), isopycnic sorting by diameter or electronic type can be achieved by single-walled CNT (SWNT). For instance, by using sodium cholate, a wide range of optically pure SWNT samples can be produced in one density gradient ultracentrifugation step. Using co-surfactants, metallic and semiconducting SWNTs can be separated. In recent work, Hersam's group has been able to obtain single chirality ultrapure (6,5) SWNTs derived from HiPCO starting material, and form thin-film transistors from these SWNTs. Hersam showed DGU of double-walled carbon nanotubes as well as electronic-type sorting of DWNT outer shell.

In the case of graphene, structurally monodisperse graphene samples are required for many fundamental studies and applications. Hersam has been able to demonstrate DGU of graphene to sort by the number of graphene layers using exfoliated graphite powder and sonication in aqueous solution with the planar surfactant sodium cholate. It has been shown that pulmonary toxicity, for instance, drops to undetectable levels when SWNTs are well dispersed using biocompatible polymers (e.g., poloxmers). Hersam described the use of biocompatible polymers rather than surfactants for DGU of graphene. DGU works very well and is scalable.

Symposium X Challenges Conventional Wisdom

The theme this year for Symposium X presentations on Frontiers of Materials Research was on challenging conventional wisdom. The question posed to the first speaker, Mildred S. Dresselhaus of the Massachusetts Institute of Technology, was "Is Nano Always the Way?" Dresselhaus explored this question by discussing the thermoelectric effect as one example. The figure of merit ZT is the critical number where T is the temperature and Z is the square of the Seebeck coefficient (S) multiplied by the electrical conductivity divided by the thermal conductivity. A limit to Z is rapidly obtained in conventional materials and the best ZT for

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bulk materials has been ~1 at 300 K because of the interrelationships between the three variables. However, low dimensional physics has yielded additional control by quantum confinement effects (quantum wells and quantum dots) and boundary scattering at interfaces (in nanocomposites, for instance). Thus nano has allowed for both an increase in electrical conductivity with a decrease in thermal conductivity, increasing *ZT*. This is a win for "nano." However, other studies have used band structure engineering to increase *S*, and thereby *ZT*, demonstrating that while nano is useful, it is not always the answer.

In addressing materials recycling, Randy Kirchain, also of MIT, posed a question to the audience asking for guesses on the per capita overall consumption of materials each day in the United States. While guesses ranged from 5–15 kg/person/day, the actual number, he said, was over 80 kg/person/day. He said that consumption strains materials systems and that, furthermore, materials and manufacturing contribute to roughly one third of the carbon release. Of the 100,000 aluminum cans used every 30 seconds in the United States, only 50% of these are recycled. Kirchain said that the materials research community can and should make a difference in the use of sustainable materials by recycling. Considering the overall materials/product cycle, the community has opportunities to improve recycling at different stages including product design, manufacture, use, disposal/recovery, and materials production. Materials researchers and engineers can make a difference particularly in the first three stages, he said.

Private and Public Funding Opportunities in Materials Research

The private sector investment in research and development (R&D) is about $1 trillion annually and is increasingly supporting innovative collaborations with start-ups, universities, and national laboratories in the generation of new energy products from materials science. In the MRS inaugural Technology Innovation Forum, organized by John Benner (The National Renewable Energy Laboratory) and Michael F. Durstock (Air Force Research Laboratory), seven companies and venture capitalists discussed the challenges and opportunities in moving invention to commercialization.

Dave Parrillo, Director R&D for Dow Solar Solutions, described how the linear progression from discrete discovery through corporate research into marketing then business development has been replaced by a quick cycle opportunity/solution space model. In the new large-business paradigm, corporate venture capital can be combined with corporate skills and internal R&D to more quickly connect technology to business.

This theme of speed-through-connection was continued by Steven Meller of The Procter and Gamble Company who described their "Connect & Develop" approach to bring as much as 50% of the new innovations into P&G from outside sources.

In a separate seminar, representing government funding for innovation, Michael Schen of the National Institute of Standards and Technology discussed opportunities for materials researchers through the Technology Innovation Program (TIP). Schen, who is scientific advisor to the director of TIP, said the program focuses on high-risk, high-reward research in areas of critical national need by teams from for-profit companies, universities, national laboratories, and others. Current topical interests include civil infrastructure, energy, health care, and manufacturing. TIP is currently seeking proposals in "Materials Advances and Critical Processes" as part of their manufacturing funding. Proposals are due July 15, 2010. Approximately $25 million is available for first-year funding for an expected 25 new TIP projects.

Energy continues to be a major government interest as the Department of Energy (DOE) seeks proposals for game-changing scientific discoveries that could alter the way energy is used, produced, and stored, as discussed by Helen Kerch of the Materials Sciences and Engineering Division, Office of Basic Energy Sciences, DOE. David Danielson, a program director for Advanced Research Projects-Energy (ARPA-E) within DOE, said topics are driven by the ARPA–E program directors and funding supports very high-risk, high-reward research and development with a focus on ultimate commercialization. He expects eight to 11 new programs in 2011.

The Department of Materials Research (DMR) division of the National Science Foundation is also rich with funding opportunities for curiosity-driven materials research. Linda Sapochak, a program director of Solid-State and Materials Chemistry divided the various programs between those that accept unsolicited proposals and programs that are solicitation-driven. The window for proposals for the unsolicited programs runs from September 1 to October 31. Among the unsolicited programs are the Individual Investigator Programs, which also consider funding for Focused Research Group (FRG) proposals comprising three or more principal investigators. Among the solicitation-driven

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Participants in the Technology Innovations Forum held during the 2010 MRS Spring Meeting.

programs is the CHE-DMR-DMS Solar Energy Initiative (SOLAR) (NSF 09-604). This is a joint initiative with other divisions at NSF which uniquely requires principal investigators from materials, chemistry, and mathematics. New on the horizon is an NSF-wide initiative focusing on Science, Engineering, and Education for Sustainability (SEES). This priority for FY2011 integrates issues of environment, energy, and economics. In a separate NSF seminar focusing on the "broader impacts" criteria of research proposals, Daniele Finotello stressed that researchers highlight mentoring opportunities in their proposals to DMR. The proposals should implement activities that go beyond normal teaching duties—activities that get people excited about careers in and the potentials of materials research. The NSF "Broader Impacts" session was sponsored by the NISE Network as well as NSF.

The U.S. Army Research Office (ARO) Materials Science Division seeks to realize unprecedented materials properties by embracing long-term, high-risk, high-payoff opportunities with special emphasis on materials design, mechanical behavior of materials, physical properties of materials, and synthesis and processing, as discussed by Division Chief David M. Stepp. The Office of Naval Research seeks research efforts in materials and early device concepts for power and energy storage, and power conversion and distribution; advanced structural materials and novel processing; and coatings and materials for prevention and mitigation of bio-fouling, and enabling affordable water purification, as described by Julie Christodoulou, director of the Naval Materials Division.

Professional Development and Networking Opportunities

MRS offered various opportunities for professional development and networking. Recognizing that scientific and engineering communities must strive to become more inclusive, engaging all demographic groups, and that diversity drives innovation, excellence, and new discoveries, MRS launched its diversity initiative with a networking reception during the Spring Meeting.

The Women in Materials Science and Engineering Breakfast, held during each Meeting, this year featured Mary Ann Mason of the University of California, Berkeley. Mason discussed analyses on women researchers who drop out of the academic pipeline and some policies put into place to offset this trend.

Tim Miller of Divine Wind LCC, who made his debut with MRS last year at the MRS Fall Meeting, demonstrated best practices in communicating science in verbal presentations. "Practice" is the key word, as Miller reiterated at the MRS Spring Meeting. He demonstrated breathing techniques as well as ways of interacting with the audience to ensure clear communication. He said that the structure of a science presentation works best when the speaker tells a story using the same elements as any story: The hero (the researcher and research group), their goal (the purpose of their research), and the series of "things" (or obstacles) happening along the way to the goal. Miller also gave various pointers on slide presentations (some of which can be found in the March 2010 issue of *MRS Bulletin*).

New this year, Miller focused one of his talks on scientific Poster presentations where he illustrated "good" and "bad" examples of posters. Some of the tips Miller gave include the use of a maximum of four colors, the choice of focusing on only one part of the research ("an appetizer," as he calls it), and a balance of text and images presented in two columns so that readers clearly know how to "read" the poster.

In making images for both verbal and poster presentations, Miller strongly recommends the use of Inkscape, an open source graphics software that can be downloaded for free. This software enables many graphic functions lacking in PowerPoint, he said.

For further details on the research results reported at the 2010 MRS Spring Meeting, see the symposium summaries posted on the MRS Bulletin Web site at www.mrs.org/BulletinS10. Proceedings as well as additional meeting highlights are available at Web site www.mrs.org/S10. MRS

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

2010 MRS Spring Meeting Reveals Integration of Various Materials Developments

Symposium Summaries

The **2010 Materials Research Society (MRS) Spring Meeting**, chaired by **Anne C. Dillon** (National Renewable Energy Laboratory), **Robin Grimes** (Imperial College London), **Paul McIntyre** (Stanford University), and **Darrin J. Pochan** (University of Delaware), was held in San Francisco on April 5–9.

Through 42 symposia, symposium organizers from around the world offered coverage of developments in the areas of

- **functional materials**, symposia A–M
- **nanomaterials**, symposia N–V
- **energy materials**, symposia W–HH
- **soft/biomaterials**, symposia II–QQ.

Following are a few highlights reported in some of the symposia, provided by the symposium organizers.

Proceedings as well as additional meeting highlights are available at Web site www.mrs.org/S10, and more symposia coverage is available in the Meeting report, "2010 MRS Spring Meeting Reveals Integration of Various Materials Developments," published in *MRS Bulletin* **35** (7) (2010).

Symposium A
Amorphous and Polycrystalline Thin-Film Silicon Science and Technology—2010

(See MRS Proceedings Volume 1245)

Thin-film silicon is a field where fundamental physics meets mainstream commercial applications. Once again, this Symposium saw a range of excellent presentations and posters from academia and industry that accurately reflected this diversity.

From a fundamental perspective, the complexity of the thin-film silicon materials was shown, which are usually either amorphous or contain a mixture of phases, as in nanocrystalline silicon, and may also include other elements, with the most notable being hydrogen. The defect creation process in amorphous silicon continues to attract significant debate, and the new insights into this process presented by H. Fritzsche (University of Chicago, retired) will no doubt continue to fuel research activity in this area.

The ever increasing importance of minimizing the human race's carbon footprint means that solar cells incorporating thin-film silicon was a key theme that ran throughout the Symposium. The ability to produce these materials on a diversity of substrates makes them attractive for applications where crystalline silicon is not appropriate. Understanding the fundamental physics of these materials is key to appreciating why protocrystalline silicon—amorphous silicon deposited close to the microcrystalline transition—is more stable in a solar cell. Presentations on methodologies for improving light trapping in solar cells attracted significant attention as did reports on improved device structures and deposition techniques. Thin film transistors for displays are another major commercial success for thin-film silicon, and the results from Princeton on amorphous silicon transistors using a new gate dielectric with a field effect mobility of ~2 $cm^2\ V^{-1}\ s^{-1}$ will be an inspiration for researchers in this field also.

Symposium Support: National Renewable Energy Laboratory, Photovoltaics Technology Center, ITRI, ULVAC Technology, Inc., and United Solar Ovonic LLC.

Symposium B
Silicon Carbide—Materials, Processing and Devices

(See MRS Proceedings Volume 1246)

Devices made from silicon carbide (SiC) possess promising advantages in high-temperature, high-power, and high-frequency applications due to its unique combination of properties (high-thermal conductivity, high breakdown voltage, and chemical stability).

Two speakers from Dow Corning discussed how dislocations have been greatly reduced over the past few years. R. Drachev showed modeling can be used to reduce the stress during physical vapor transport (PVT). D. Hansen gave experimental evidence that basal plane dislocations (BPDs), threading edge dislocations (TEDs), and threading screw dislocations (TSDs) have been greatly reduced in both 76 mm and 100 mm SiC wafers during the PVT process (down to the 100's/cm^2 levels). M. Dudley (SUNY Stony Brook) showed an extensive examination of these dislocations converting or switching from one type to another. In particular he observed TSDs, TEDs, and dislocations with Burgers vector of $\mathbf{c} + \mathbf{a}$ converting into Shockley and Frank type partial dislocations on the basal plane of various Burgers vectors and stacking faults. He presented a model that explained how the transformation can take place. This is a significant finding for if this conversion can be controlled, threading dislocations can be even further reduced in PVT-growth SiC wafers.

Some presentations related to the interaction of biological systems/tissue to SiC surfaces which may form the basis for advanced biomedical devices such as sensors and implants. S.E. Saddow (University of South Florida) assessed the biocompatibility of SiC and reported that single-crystal SiC is biocompatible and may be hemacompatible. Work performed to use fluorescent markers of SiC that are ingested in cells was presented by J.-M. Bluet (Lyon Institute of Nanotechnology). This work was very promising since the fluorescence can be activated over very long time intervals. The functionalization of SiC surfaces through self-assembled-monolayers was presented by I. Sharpe (Institute Technische Universität München) and the results show that SiC can be functionalized for specific detection of various biological and (not presented) chemical species.

Other highlights from this Symposium can be found in the July 2010 issue of *MRS Bulletin*, including presentations on ion implantation by H. Tsuchida (CRIEPI) and D.A. Schoner (Acreo AB).

Symposium Support: Cree, Inc. and Dow Corning Semiconductor Solutions.

Symposium C
Solution Processing of Inorganic and Hybrid Materials for Electronics and Photonics

(See MRS Proceedings Volume 1247E)

By combining solution processing with an additive patterning technology, it is hoped that vital advances in reducing costs and improving performance can be made for a range of devices, such as photovoltaics (PVs) and electronic displays. Topics covered in this Symposium include quantum dots, transparent conductive oxides (TCOs), organic–inorganic hybrids,

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materials for PVs, and various patterning routes such as inkjet printing.

D. Talapin (University of Chicago) opened the discussion on nanoparticles (NPs), focusing on reducing the negative contribution on end device performance made by the ligands that are used to stabilize the NPs; his group's research is examining the replacement of organic-based with inorganic-type ligands. L. Amirav (standing in for P. Alivisatos, University of California, Berkeley) introduced the concepts of nanorods for use in solar power and fuel cells, with the Pt-tipped CdS nanorod producing promising results for H_2 production. Additionally, interesting nanoparticle-based device results were presented by E. Sargent (University of Toronto), who discussed quantum-size-effect tunability and the application of this effect in light detection and PVs. An overview of the sintering mechanisms taken by NPs was provided by V. Subramanian (University of California, Berkeley); such an understanding is necessary for TCOs and the metal inks that are typically used in interconnects.

L. Eldada (Heliovolt) opened a session on solution-based processing for PVs, giving an update on the business landscape for copper-indium-gallium-selenide (CIGS) technology, as well as describing the latest device results using the Heliovolt FASST printing process (14% efficiency for single cells, 10% for 2 ft. × 4 ft. modules). R. Bhattacharya (National Renewable Energy Laboratory) gave an update on electrodeposited CIGS devices, including 12.5% modules processed at Solopower with ~100 cm^2 area and 10% modules with ~1 m^2 area.

A variety of talks focused on patterning techniques such as inkjet printing (S. Yeates, University Manchester, UK), laser direct write (J. Wang, Naval Research Laboratory), and continuous filament writing (J. Lewis, University of Illinois, Urbana-Champaign). Advances in feature resolution, final materials performance, and new applications were given.

Symposium Support: IBM T.J. Watson Research Center.

Symposium F
Materials, Processes, Integration, and Reliability in Advanced Interconnects for Micro- and Nanoelectronics
(See MRS Proceedings Volume 1249)

The pace of the semiconductor industry to achieve device requirements for 32 nm node technology and beyond creates a demand for new and improved materials and materials processing. These innovations are vital to maintain the reliability of interconnects for leading-edge semiconductor chips and devices. The speakers in this Symposium tackled a broad range of issues including novel dielectric materials, copper migration, plasma damage, and carbon nanotube devices. Z. Tokei (IMEC) opened the Symposium with an overview of the challenges related to interconnect reliability at all levels. He also presented work from IMEC that is focused on developing a nanoprobe system for characterizing and understanding dielectric breakdown. S. Ono (Mitsui Chemicals) highlighted the company's recent progress to develop thin polymer-based layers that can act to seal the pores of low-*k* films. These materials have the potential to be a simple solution to inhibit copper migration into the dielectric layer. C. Soles (National Institute of Standards and Technology), J. Watkins (University of Massachusetts, Amherst), and Q. Lin (IBM) presented alternative methods for producing and patterning low-*k* dielectrics. While the IBM work employs traditional photolithographic tools to directly pattern the dielectric layer, the NIST group directly forms patterned low-*k* dielectrics using nanoimprint techniques, and the group at UMass utilizes block copolymer self-assembly to produce ultralow-*k* materials. These innovations represent progress toward addressing the challenges facing interconnects for micro- and nanoelectronics.

Symposium Support: IBM Almaden Research Center; JSR Micro, Inc.; and Tokyo Electron of America, Inc.

Symposium G
Materials and Physics of Nonvolatile Memories
(See MRS Proceedings Volume 1250)

T. Baron (LTM-CNRS) and H.-T. Lue (Macronix Int. Co.) summarized the current status of nanocrystal and advanced three-dimensional charge-trapping Flash memories. Lue overviewed the trends and the future device architectures as designed by the companies in the field of nonvolatile memory Flash memories. A session on magnetic random-access memory was given, and Y. Roizin (Tower Semiconductors) presented the past and the future of Flash-type memory devices.

Organic memories represent a new highly potential area. Their integration using crossbar architecture seems still the best choice when the active cells are connected in series with a diode. However, very attractive and promising results were presented by T.N. Ng (Palo Alto Research Center), utilizing ferroelectric polymers on the gate of organic transistors. The ensemble of the memory cells were realized by inkjet printing. In the area of resistive memories (ReRAM), S. Spiga (MDM CNR-INFM) addressed nickel and titanium oxides.

Three speakers gave excellent overviews on the area of resistive and ionic memories: C.H. Hwang (Seoul National University), with his pioneered work, answered to the question on the nature of the filaments which are responsible for the resistivity switching; M.N. Kozicki (Arizona State University) described the operational aspects of cation-based memories; and D. Wouters (IMEC) gave a clear view about the prospects and the challenges of resistive memories.

D. Takashima (Toshiba Corp.) and K. Miyaji (University of Tokyo) addressed ferroelectric random-access memories, discussing the current status, trends, and benchmarking in real applications. In the area of phase-change random access memories, several specialists presented talks from the nonvolatile random-access memories and phase-change materials fields.

Symposium Support: Annealsys, Park Systems Corp., WACOM R&D Corp., and Universal Systems.

Symposium M
Structure-Function Relations at Perovskite Surfaces and Interfaces
(See MRS Proceedings Volume 1255E)

Interfaces, boundaries, and surfaces of perovskite oxides often modify the well-known hysteretic and coupled responses of these materials to electric, magnetic, and stress stimuli. This Symposium focused on the relationships between atomic-scale structures of surfaces and interfaces and the functional properties of perovskite oxides in both experimental and theoretical works.

One topical issue was the understanding and application of 2D electron layers formed at heterointerfaces between $LaAlO_3$ and $SrTiO_3$. Several research groups raised the possibility of instability and intermixing at these interfaces depending on the film growth conditions. Recent analytical methods such as aberration-corrected electron microscopy, x-ray diffraction, and scanning probe microscopy combined with density-functional theory are starting to tackle this fundamental issue. However, the film growth processes, which can control defect formation and the stoichiometry of perovskite materials, will be crucially important in answering these questions. Regardless of the exact mechanisms, the finding of mobile electrons at interfaces of insulating oxides is intriguing to many researchers.

A second highlighted topic was that of interfaces in multiferroic perovskite oxides. Again, recent advanced characterization techniques combined with density-functional theory calculations are proving

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to be powerful tools for understanding electric, elastic, and magnetic properties of these promising but complex materials. Examples were given of control of these properties through their nanoscale interfaces, defects, and effects of low-dimensionality. Notable topics included the surface chemistry and its influence on thin multiferroic films, direct imaging of interface polarization with scanning transmission electron microscopy, magnetic properties, and electrical transport at domain interfaces.

Symposium Support: Asylum Research, CrysTec GmbH, Surface Systems & Technology GmbH & Co. KG, UT Battelle—Oak Ridge National Laboratory, and University of Tokyo, Institute of Engineering Innovation.

Symposium N
Functional Oxide Nanostructures and Heterostructures
(See MRS Proceedings Volume 1256E)

Oxides remain the richest class of materials in terms of physical, chemical, and structural properties. They exhibit a very broad range of functionalities based on their magnetic, dielectric, piezoelectric, semiconducting, superconducting, thermal, mechanical, optical, photoelectrochemical, and catalytic properties, and often offering a combination of those properties. This Symposium addressed the most promising synthesis methods as well as the fundamentals and applied aspects of the physics, chemistry, and engineering of hetero- and nanostructured functional oxides. A plethora of applications of such advanced structures and devices were presented which included, for instance, low-cost superconductors (Hosono), piezotronics (Wang), resistive memory devices (Mehta), TCOs, second-to-third-generation PVs (Tachibana), miniaturized solid-oxide fuel cells (Traversa), ultrathin solar absorbers (Westin), single nanowire sensors (Fischer), and cost-effective nanorod-based photocatalysts for solar hydrogen generation (Warren, Kronawitter, Wang). The role and importance of experimental growth control (Wong), structure–property relationships (Ohta, Janek, Arenholz, Mahendiran), defect chemistry (Rothschild, Batzill), and surface and interface phenomena (McHenry, Majetich) as well as size-dependence and nanotoxicity (Hemmer, Ramanujan) was also covered.

Symposium Support: Army Research Office and Institut National de la Recherche Scientifique.

Symposium O
Multifunctional Nanoparticle Systems—Coupled Behavior and Applications
(See MRS Proceedings Volume 1257)

Multifunctional nanoparticle systems integrate multiple functional inorganic or organic building blocks, thus providing improved or new material properties unavailable from a single component. A key focus of Symposium O was the development and demonstration of multifunctional nanoparticles for biomedical applications. Y.N. Xia (Washington University), X. Gao, (University of Washington, Seattle), and B. Gates (Simon Fraser University) discussed approaches for photothermal-triggered drug delivery using gold-containing nanostructures. C.J. Murphy (University of Illinois, Urbana-Champaign) presented a discussion of the issues associated with biological labeling of nanoparticles, including nanoparticle surface chemistry, cellular uptake, and cytotoxicity. Several new concepts and applications were introduced in this Symposium, including new techniques for imaging magnetic nanoparticles with minimal biological background interference (K.M. Krishnan, University of Washington, Seattle) and magnetic nanoparticles for biodiesel production from algae (V.S.Y. Lin, Iowa State University).

Many talks in a session on catalysis focused on designing novel, integrated nanostructures to improve the catalytic performance of Pt in the oxidation reduction reaction, such as alloys, core/shell, and porous structures. During the multifunctional polymers session, J. Pyun (University of Arizona) described the synthesis of Au(core)/Co_3O_4(shell) nanowires through colloidal polymerization, which have great potential for lithium-ion batteries and supercapacitors. M.R. Bockstaller (Carnegie Mellon University) presented the assembly of polymer-grafted nanoparticles with polymer brushes of different lengths, which enabled refractive index matching. He also discussed how the polymer brush length affects nanoparticle self-assembly, thus demonstrating tuning between the limits of hard and soft behavior.

Symposium Support: Army Research Office.

Symposium P
Semiconductor Nanowires—Growth, Physics, Devices, and Applications
(See MRS Proceedings Volume 1258)

This Symposium presented the most recent results and breakthroughs and discussed similarities but also differences between the various classes of materials such as Si, Ge, III–Vs and II–VIs. The Symposium covered basically all aspects of NW science and technology—from growth to applications for future post CMOS devices.

In her opening lecture, R. Calarco from Research Center Jülich, Germany presented the doping effect of Si and Mg on the crystalline, optical, and electrical properties of InN nanowires (NWs) in comparison to undoped counterparts. Electrical measurements on a large number of single contacted NWs of different dimensions demonstrated that the carrier transport mainly takes place in a tube-like surface electron gas. Nanowires composed of group III–V materials are of particular interest for applications. T. Fukui (Hokkaido University, Japan) demonstrated single GaAs/GaAsP coaxial core/shell NWs showing lasing as well as PV devices and the fabrication of vertical surround-gate field-effect transistors (VSGFETs). C. Thelander (Lund University, Sweden) evaluated the *n*-doping for InAs NWs and demonstrated vertical transistor devices with high-*k* gate dielectrics and wrap-around gates. For Si NWs, the growth conditions, doping strategies, and critical processing steps for tunnel FETs were reported by M.T. Bjoerk (IBM Research Zürich, Switzerland). In addition, E. Tutuc (University of Texas, Austin) discussed epitaxially grown Ge-Si_xGe_{1-x} core/shell NW heterostructures and their use for high-performance FETs.

Fundamental physical limits with NWs and nanomesh films for superconducting applications were discussed by J.R. Heath (California Institute of Technology). V. Schmidt (Max Planck Institute, Halle) focused on the growth of InSb and R. Agarwal (University of Pennsylvania) discussed the effect of NW size on various properties.

Symposium Support: FEI Deutschland Gmb; IBM Zurich Research Laboratory; Oxford Instruments Plasma Technology; Raith USA, Inc.; and Vistec.

Symposium Q
Template-Based Nanofabrication: Nanowires, Nanotubes and Associated Hetero-Nanostructures
(See MRS Proceedings Volume 1258)

Among various methods to controlled nanofabrication, the template-assisted methods, which are less-costly than others and reproducible, and usually have a high-yield, appear to be successful for the fabrications of a large variety of nanostructures including wires, tubes, hollow particles, heterogeneous, or hybrid materials. This Symposium focused on the preparation and modification of appropriate templates and the template-assisted fabrication strategies.

Nanotubes are fabricated in new ways. Hydrothermal growth has been a widely used method for nanowires of various materials such as ZnO. Worldwide, every group obtained short ZnO nanorods until the S. Jin group recently discovered that,

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

by applying a much smaller solution supersaturation, ZnO nanotubes are formed instead of solid nanorods. Their phenomenon is supported by an old crystal growth theory, and the driven force for nanotubes formation is claimed to be dislocations. Latest progress on inorganic fullerene-like nanotubes was summarized by R. Tenne (Weizmann Institute, Israel), who also showed their recent discovery of core/shell nanotubes such as $PbI_2@WS_2$. The P. Yang group at the University of California, Berkeley, reported GaN-ZnO alloy nanotubes fabricated through a nanowire-templated interface reaction. Promising application of these alloy nanotubes in H_2 generation from water was demonstrated.

One particular interesting topic is the application of atomic layer deposition (ALD) in nanofabrications. S. George (University of Colorado) shared their research on In_2S_3 ALD as a sensitizer on TiO_2 nanotube array for solar energy conversion. K. Nielsch (University of Hamburg) elaborated on ALD of magnetic nanotubes of Ni, Co, and Fe_2O_3 inside high-aspect-ratio alumina membranes, which allows an accurate study of tube wall thickness-dependent magnetic properties for data storage application. M. Knez (Max Planck Institute, Halle) focused on ALD fabrications with bio-templates as exemplified by spider silk whose strength can be significantly enhanced by ALD metal layers.

Knez also gave a tribute to U. Gösele, former director of Max Planck Institute of Microstructure Physics, Halle, who deceased unexpectedly in November 2009. Gösele's intuition and creativity led to an omnipresence of himself and his coworkers on MRS meetings for many years. Gösele has a big name in diffusion phenomena in semiconductors and wafer bonding. He later extended his research topics to nanowires and nanotubes of numerous materials using templates including porous alumina membranes, block copolymer structures, and nanowires of appropriate materials.

Other highlights from this Symposium can be found in the July 2010 issue of *MRS Bulletin*, including a review on Si nanowires presented by S.T. Lee (City University of Hong Kong).

Symposium Support: Beneq Oy; Cambridge Nanotech, Inc.; J.A. Wollam Co., Inc.; Kurt J. Lesker Co..

Symposium T
Photovoltaics and Optoelectronics from Nanoparticles
(See MRS Proceedings Volume 1260)

Nanoparticles are typically of dimensions between 1 nm and 100 nm. Their electronic and optical properties are significantly different from bulk materials and adjustable by varying their size. This class of materials covers the regime between atoms or molecules and macroscopic solids and forms the precursor to a wealth of innovative applications. However, a sustainable transfer of fundamental and applied scientific knowledge into marketable products is mostly still missing. The Symposium focused on *conversion of electric energy into light* and *conversion of light into electric energy* by making use of nanoparticles. Corresponding optoelectronic and photovoltaic devices are not realized through the usual lateral structures on semiconductor single crystals, but instead by using disperse systems of nanoparticles as optically active materials. This opens a new path to printable devices.

Solution-based printing and coating processes have the potential to dramatically reduce production costs of photovoltaics. These include not only organic photovoltaics, but also a variety of devices based on metal and semiconductor nanocrystals inks. M.T. Swihart (State University of New York) studied silicon nanocrystal-based photovoltaic devices. Silicon is nontoxic, abundant, and the dominant material currently used in photovoltaics. He has developed a laser pyrolysis method for producing Si nanocrystals with a primary particle size as small as 5 nm. The as-synthesized particles are aggregated and partially sintered. These can be separated and reduced in size by acid etching, and can be made soluble in organic solvents by using hydrosilylation reactions to attach organic molecules to their surface.

Hybrid materials combine the low-cost, large-area processing notable of organic materials and the tunable, optical and electronic properties found in nanoscale inorganic materials. C. Kagan (University of Pennsylvania) combined nanostructures with solution-processable organic semiconductors such as poly-3-hexyl thiophene and a solution-processable precursor that is thermally retro-converted to red-absorbing, high-mobility pentacene that allows us to fabricate organic–inorganic bulk heterojunctions.

Complete surface passivation is critical for the best use of confinement effects of nanosilicon. N. Koshida of Tokyo University of Agriculture and Technology applied high-pressure water vapor annealing to nanosilicon prepared by electrochemical anodization and demonstrated the external quantum efficiency of the red photoluminescence reached 23% at room temperature.

H. McDaniel and M. Shim (University of Illinois, Urbana-Champaign) demonstrated that a careful examination of type II nanocrystal heterostructures of CdSe/CdTe system using high-resolution transmission electron microscopy and scanning transmission electron microscopy techniques allow for a spatial mapping of the composition which is then correlated with electronic and optical features.

Symposium Support: 3 M Co.; Argonne National Laboratory; Energy & Environmental Science, *Royal Society of Chemistry; Evonik Degussa GmbH; GE Global Research; and Los Alamos National Laboratory.*

Symposium AA
Scientific Basis for Nuclear Waste Management XXXIV
(See MRS Proceedings Volume 1265)

Presentations in this Symposium gave insight into the (international) politics of nuclear waste management and showcased the breadth and depth of current research and technology development.

The importance of waste management were exemplified by presentations that addressed the closure of the Yucca Mountain project (P. Swift, Sandia National Laboratories), the likely mechanism for future repositories in the United States (W.M. Nutt, Argonne National Laboratory), and the experience of Sweden in the search for their repository (L. Werme, Uppsala University, Sweden). These presentations contrasted with a historical view of and potential vision for nuclear waste management in the United States (R.C. Ewing, University of Michigan).

Presentations on current nuclear waste technologies included new materials for immobilizing technetium (K. Sickafus, Los Alamos National Laboratory), the deterioration of spent nuclear fuels (V.V. Rondinella, Institute for Transuranium Elements, Germany), and the long-term stability of Pu-containing materials in aqueous conditions (P. Poeml, Institute for Transuranium Elements, Germany). One new area of research highlighted was the use of simulations to predict the effects of beta decay on the stability of materials, specifically the change from Cs+ to Ba+ and how it affects the material in the long term (C.R. Stanek, Los Alamos National Laboratory). This discussion led to one on how this effect could be used to prepare new materials with unique properties.

In a joint session with Symposium BB, speakers highlighted the effects of radiation damage on waste forms and discussed how they can be mitigated and used in future repository safety assessments. The joint session with Symposium

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

Z showed how understanding the basic chemistry of actinides helps not only developing new waste form materials, but also how the materials will behave under repository conditions.

Symposium Support: Australian Nuclear Science and Technology Organisation, CEA, and Los Alamos National Laboratory.

Symposium CC Solid State Batteries

(See MRS Proceedings Volume 1266E)

This Symposium presented recent progress in solid-state Li-ion batteries. A. Hayashi (Osaka Prefecture University, Japan) discussed the development of sulfide glass-based electrolytes. Their all-solid-state batteries Li-In/$LiCoO_2$ using the Li_2S-P_2S_5 glass-ceramic electrolytes showed excellent cyclability for 700 cycles at a limited current density. Surface coating $LiCoO_2$ with an oxide buffer layer such as $LiNbO_3$ and Li_2SiO_3 was reported to improve rate performance of all-solid-state batteries. For the first time known, Hayashi also reported on the TEM observation of the solid–solid interface between $LiCoO_2$ electrode and Li_2S-P_2S_5 electrolyte. The mutual diffusion and the formation of the interfacial layer were suppressed using $LiCoO_2$ particles coated with Li_2SiO_3 thin film. Interfacial structure and battery performance for several active materials including $LiCoO_2$ was also discussed.

S. George (University of Colorado) discussed atomic layer deposition (ALD) coatings to enhance the performance of Li-ion batteries. Cathodes prepared using $LiCoO_2$ powders coated with Al_2O_3 ALD films exhibited higher stability. The capacity retention was 89% after 120 charge-discharge cycles in the 3.3–4.5 V (versus Li/Li^+) range compared with bare $LiCoO_2$ powders that displayed only a 45% capacity retention. Graphite electrodes with Al_2O_3 ALD films coated directly also displayed dramatically improved performance and 98% capacity retention was observed after 200 charge-discharge cycles. Other Li-containing ALD films were suggested to provide performance improvement. The ALD of an artificial solid electrolyte interphase layer may limit lithium loss and also improve the capacity stability during charge-discharge cycles.

Other highlights from this Symposium can be found in the July 2010 issue of *MRS Bulletin*, including a review by R. Kanno (Tokyo Institute of Technology, Japan) on the current status of solid-state inorganic electrolytes, which are critical components for the successful development of solid-state Li-ion batteries.

Symposium DD Thermoelectric Materials—Growth, Properties, Novel Characterization Methods, and Applications

(See MRS Proceedings Volume 1267)

Thermoelectric materials have gained significant attention as energy-conversion materials in order to recycle waste heat from power plants, automobiles, and computers into usable electrical energy. While the first such practical material (bismuth telluride alloy) was prepared nearly 40 years ago, only recently has there been progress in realizing thermoelectric materials with significantly improved efficiencies with a key driver behind this success being the ability to structure materials at the nanoscale. This Symposium brought together researchers developing novel materials and preparation methods, characterization techniques, and applications of thermoelectric materials. Topics addressed in the Symposium included processing and properties of bulk and thin-film thermoelectric materials, nanostructured complex oxide materials, organic–inorganic hybrid materials, nanoscale energy transport and conversion, *ab initio* studies and the design, fabrication, and testing of thermoelectric devices.

In the opening session, D.G. Cahill (University of Illinois, Urbana-Champaign) focused on the thermal conductivity of materials, investigating the thermal conductivity of a wide variety of nanostructured thermoelectric materials including InGaAs/ErAs nanodots and PbTe/PbSe nanodots superlattices by time-domain thermoreflectance (TDTR). ErAs nanodots lowered the thermal conductivity of InGaAs and reduced the TDTR frequency dependence while PbSe nanodots were not as effective in lowering the thermal conductivity of PbTe. The lattice thermal conductivity of PbTe/PbSe nanodots superlattices did not fall significantly below 1 W/m K. This was understood based on the small acoustic mismatch between PbTe and PbSe and the strong anharmonicity of PbTe.

In the area of applications of thermoelectric materials, R. Funahashi (National Institute of Advanced Industrial Science and Technology) discussed power generation of cascaded thermoelectric arrays and S. Funahashi (Murata Manufacturing Company, Ltd.) reported progress on the development of thermoelectric devices using a multilayer ceramic capacitor production technology. The thermoelectric device consisted of 25 P/I/N—pairs using *p*-type- $(La_{1.97},Sr_{0.03})CuO_4$, *n*-type- $(Nd_{1.97},Ce_{0.03})CuO_4$, and an insulator with a mixture of Mg_2SiO_4 and glass. The device generated 26 mW of electric power with 360 K of temperature gap. Generated electric power was smaller than the theoretical value because of electric resistance and thermal losses in the *p*/*n*-junction. Adjustment in the fabrication process such as the densities of green tape, laminated density, and sintering condition improved the performance of the thermoelectric multilayer ceramic capacitors.

Studies on the development of novel thermoelectric materials covered both oxide and nonoxide materials in bulk and thin film form. In the area of bulk nonoxide thermoelectric materials, C. Uher (University of Michigan) gave an update on recent progress in Skutterdite-based thermoelectrics while E.S. Toberer (California Institute of Technology) presented studies on transport in complex Zintl antimonides. T. Ikeda (PRESTO and California Institute of Technology) discussed nanostructure formation in bulk PbTe-based compounds through phase transformation. Progress in materials research on thermoelectric oxides was presented by K. Koumoto (Nagoya University) who focused on nanostructure control to enhance thermoelectric performance of $SrTiO_3$ and TiS_2 2DEG and A. Wedenkaff (Solid State Chemistry and Catalysis, EMPA, Duebendorf, Switzerland) who discussed development of perovskite-type oxide and oxynitrades for thermoelectric solar converters.

Symposium Support: Corning, Inc.; GMZ Energy, Inc.; Nanonics Imaging Ltd.; and ZT Plus.

Symposium EE Defects in Inorganic Photovoltaic Materials

(See MRS Proceedings Volume 1268)

Because defects in photovoltaic (PV) materials play a key role in determining materials properties critical to PV application, improved understanding and control of defects gives the potential to enable new classes of PV materials, paving the way for future generations of solar cells. Following are a few highlights of presentations given in this Symposium.

One discussion focused on the Cu_2ZnSnS_4 (CZTS) compound as an earth-abundant PV material. With 8% efficiency now, it has the potential to replace $CuInGaSe_2$ (CIGS) thereby eliminating the dependence on (expensive) indium. S.-H. Wei (National Renewable Energy Laboratory) introduced the problem from a theoretical perspective. Surprisingly, the physics of defects in CZTS is qualitatively different from that in CIGS. On the experimental side, several researchers discussed how to identify secondary phases, which is a natural drawback for quaternary alloys. It was shown that impurity doping such as

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

sodium and growth rate can have dramatic effects on the quality of the CZTS films. I. Bhat (Rensselaer Polytechnic Institute) discussed the use of inexpensive glass or metal substrate for epitaxial growth of thin-film solar cells. If the technique can be demonstrated for reasonably high-efficiency solar cell fabrication, the work would open a new direction for photovoltaics.

Even in very well-established materials such as Si, new insights are possible. R. Grimes (Imperial College) showed that Pauling electronegativities predict donor dopants in Si to act as acceptors and vice versa and that this contradiction disappears if clusters of dopant plus four neighboring Si atoms are considered (versus pure Si clusters) instead. This finding, which is supported by full electronic structure calculations, illustrates not only that it is charge redistribution between the dopant and its cluster of neighbors that dopes the Si, but once again that Pauling is (nearly) always right.

In other highlights, D. Cahen (Weizmann Institute of Science) talked about using the dipoles of adsorbed polar molecules on semiconductors. Beneficial effects can be obtained even from very small molecules. C. Taylor (Colorado School of Mines) gave an overview of progress in amorphous silicon solar cells and presented electron spin resonance investigations of dangling bonds. J. Heath closed the Symposium by presenting a study of grain boundaries in mc-silicon using scanning capacitance probe microscopy.

Other highlights from this Symposium can be found in the July 2010 issue of *MRS Bulletin*, including a presentation by J. Ager (Lawrence Berkeley National Laboratory) who opened the Symposium with a discussion of the role of defects in shaping three new and emerging PV materials.

Symposium GG
Nanoscale Charge Transport in Excitonic Solar Cells
(See MRS Proceedings Volume 1270)

Organic solar cells (OSC) have attracted worldwide attention from the research community due to their potential to replace traditional Si-based solar cells. Their low-cost and ability to be integrated with practically any surface (rooftops of bus stations to backpacks and umbrellas) makes OSCs an important technological path. Current OSC technologies produce cells with about 6–8% efficiency while commercialization of these technologies requires 10–13% efficiency. This Symposium brought together researchers developing novel materials, device technologies, and approaches to study nanoscale charge transport processes that address current challenges to reach 10–13% efficiency. Two joint sessions with Symposia HH and II highlighted key recent developments in organic photovoltaics (OPVs).

A.J. Heeger (University of California, Santa Barbara) addressed the need to develop nanoscale morphologies that can efficiently collect a majority of charge carriers. He described processes and materials that can lead to a cross-over from monomolecular recombination, which dominates at short circuit conditions, to bimolecular recombination that dominates at open circuit conditions. Using detailed experimental results, supported by theoretical simulations, Heeger concluded that monomolecular recombination is due to interfacial traps, whereas bimolecular recombination is due to band-to-band recombination.

R.A. Street (Palo Alto Research Center), A. Pivrikas (Linz Institute), and N. Tessler (Israel Institute of Technology) debated modeling and theoretical approaches that can explain nanoscale charge transport processes and their connection to macroscale efficiency of OSCs.

Symposium Support: Office of Naval Research and National Science Foundation.

Symposium MM
Evaporative Self-Assembly of Polymers, Nanoparticles, and DNA
(See MRS Proceedings Volume 1273E)

This Symposium featured presentations on the use of dewetting phenomena to control nano- and microscale structure. There has been a rapid growth in interest in exploiting the evaporation of a solvent to "imprint" various dewetting patterns on a solute and the invited and contributed talks presented a comprehensive snapshot of the state of the art in the field. E. Rabani (Tel Aviv University), U. Thiele (Loughborough, U.K.), H. Jaeger (University of Chicago), and B.A. Korgel (University of Texas at Austin) focused on the array of patterns formed by nanoparticles/nanorods when deposited from volatile solvents. Jaeger presented advances in the field involving the production of free-standing nanoparticle monolayers (comprising many millions of particles) and the subsequent measurement of their mechanical properties while Korgel focused on key developments in harnessing the complexity of nanoparticle/nanorod assembly. K. Stebe (University of Pennsylvania), like Korgel, discussed the role of particle shape in determining interparticle interactions but focused on the intriguing properties of nanocylinders at fluid interfaces.

Developments in exploiting colloidal building blocks for plasmonic materials were presented by P. Yang (University of California, Berkeley) who discussed how self-assembly of Ag nanoparticles could be used to prepare metamaterials whose optical properties could be tuned simply by varying the volume fraction of the particles.

T. Russell (University of Massachusetts, Amherst) showed the degree of long-range order possible for microdomains of block copolymers—single "crystal" domains up to 10 × 10 μm²—following annealing under solvent vapor. A wide range of different methods were presented for controlling the structure formed by a drying droplet spanning slip-stick motion of the contact line using confined solution geometries, convective assembly, liquid capillary microbridges, and breath figure templates. Many of these methods, despite their simplicity, produce structures that are as highly ordered as those produced by significantly more complex (and expensive/time-consuming) lithographic techniques.

Symposium Support: Argonne National Laboratory; Asylum Research; College of Engineering, INHA University, Korea; Institute of Physics, Nanoscale Physics and Technology Group, UK; and Institute of Physics, Thin Films and Surfaces Group, UK.

Symposium NN
Materials Exploiting Peptide and Protein Self-Assembly—Toward Design Rules
(See MRS Proceedings Volume 1272)

Nature has evolved a variety of creative approaches to many aspects of materials synthesis and microstructural control. One such approach is self-assembly, which represents a simple and efficient route to the construction of large, complex structures.

In this Symposium, a diverse set of researchers from academia and industry discussed recent advancements in the design of self-assembling systems, particularly those based on proteins and peptides. A common theme was the elucidation of design rules that can be developed to predict the assembly, physical properties, and biological properties of such materials.

Researchers discussing the assembly of peptides or peptide derivatives included S.I. Stupp (Northwestern University), K.L. Kiick (University of Delaware), A. Miller (University of Manchester, UK), R.V. Ulijn (University of Strathclyde, UK), I. Hamley (University of Reading), A. Banerjee (Indian Assoc. for the Cultivation of Science), E. Gazit (Tel Aviv University), and D. Pochan (University of Delaware). These presentations addressed topics ranging from the use of peptide amphiphiles in regenerative medicine (Stupp) to the behavior of amyloid peptide-polymer conjugates (Hamley) to biocatalytic induction of assembly (Uijjn).

Researchers addressing the assembly of

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press

proteins included T. Scheibel (Universitat Bayreuth), who discussed his recent work elucidating aspects of spider silk spinning, and P. Gilbert (University of Wisconsin), who discussed processes involved in the formation of natural biominerals.

Symposium Support: Cambridge Research Biochemicals, UK; C S Bio Co., Inc.; EPJ E Soft Matter & Biological Physics*; Hecus X-Ray Systems GmbH; Peptisyntha, a subsidiary of Solvay; and Setaram, Inc.*

Symposium OO
Hierarchical Self-Assembly of Functional Materials from Nanoscopic- to Mesoscopic-Length Scales

(See MRS Proceedings Volume 1272)

Sublithographic patterning of functional materials continues to be a challenge. One theme running through this Symposium was that sublithographic one-dimensional structures are easily accessed by using lithography to pattern a strained film in two-dimensions, and letting it wrinkle or roll up spontaneously into a tube or helix. The range of materials and applications for this approach were many and varied. S. Harazim (Leibniz Institute for Solid State and Materials Research, Dresden) showed how wrinkled InGaAs films could be used to form 25 nm diameter nanochannels, 6 μm in length. These tubes may be useful for nanofluidics; Harazim demonstrated their use to construct an ion-sensitive field-effect transistor. S. Mendach (Institute of Applied Physics, Hamburg) demonstrated Ag/InGaAs rolled up into "jelly rolls," which act as metamaterial hyperlenses for which the relative thickness of the Ag and InGaAs layers can tune the working wavelength over a broad range in the visible and near infrared. L. Zhang (Swiss Federal Institute of Technology, Zürich) showed the magnetic actuation of "helical nanobelts" and turned them into low Reynolds number swimmers that corkscrew through water like a spirochete.

DNA nanostructures, and in particular DNA origami, now allow the programmed self-assembly of arbitrary structure at the nanoscale. One theme of this Symposium was the extension of two-dimensional origami to three-dimensions, and the applications enabled by this. W.M. Shih (Harvard) presented a method for creating 3D origami on a honeycomb lattice, and the application of hexagonal DNA rods to nuclear magnetic resonance of membrane proteins. E.S. Andersen (Aarhus University) presented the construction of a DNA origami box with an actuatable lid that can be used to prevent or allow access of an enzyme to a substrate sequestered within the box; in the future the box may be used for programmable drug delivery.

Other highlights from this Symposium can be found in the July 2010 issue of *MRS Bulletin*, including a presentation by T.G. Mason (University of California, Los Angeles) who reported on the depletion attraction-mediated self-assembly of lithographic particles.

Symposium Support: National Science Foundation, Office of Naval Research, and Veeco Instruments.

https://doi.org/10.1557/mrs2010.605 Published online by Cambridge University Press