Silicon solar cells – wafers and thin films

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Why do we work on thin-film solar cells? We get an answer by inspecting the function of a silicon wafer solar cell and identifying its shortcomings. To make silicon cells cheaper we will reduce the thickness of the wafer. The high cost of thinning wafers makes us switch from making wafers to depositing micrometer-thick films. But layers made on affordable substrates are defective. The many defects force us to make the cells electrically thin, so that photogenerated charge won't die on its way to collection. Here the various optical absorption spectra of semiconductors make our road to thin-film cells branch into three paths. Amorphous and nanocrystalline silicon cells must be made very thin to ensure carrier collection by drift; because silicon doesn't absorb sunlight well, we must resort to all kinds of tricks to trap the light. The solar-successful inorganic compound semiconductors [CdTe, $Cu(In,Ga)Se_2$] absorb sunlight within their electrical charge collection length. The iconicity of these compounds makes their solar cells fairly insensitive to defects, drift and diffusion are equally important, and light management techniques are fairly conventional. Absorption of sunlight in organic semiconductors generates excitons; therefore organic solar cells must be made as ultra-thin heterodiodes, and the carriers again rely on collection by drift -- thin is doubly important for organics. The purpose of this introductory lecture is to position the various thin-film solar cell technologies in the light absorption – carrier collection space, with some emphasis on using silicon for illustration.

Chalcogenide thin film solar cells: the lowest cost per Watt solar technology

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Chalcogenide solar cells based on CdTe, $Cu(In,Ga)Se_2$ (CIGS), and related materials were dismissed alternately as ancient or failed technologies with no chance of catching up to crystalline Si only six years ago. Since that time CdTe manufactured by First Solar has emerged as the world's lowest cost device (nearly 40% lower cost/W to manufacture than crystalline Si) and First Solar is now the world's largest solar module manufacturer, expected to exceed 2.2 GW annually in 2012. Encouraged by this success many other companies are rethinking CdTe as a technology. At the same time, CIGS has exceeded 20% efficiency in single-junction champion cells and 14% in manufactured modules. Manufacturing is scaling up. Showa Shell has announced opening of a 1 GW (nameplate capacity) plant and major scale up is underway as well at Solibro/Q-Cells, Nanosolar, and many others. The science of chalcogenide devices shows major potential for further improvements. The chalcogenide family of semiconductors includes a broad spectrum of soluble alloys that can access optimal energy gaps for single-junction cells. At the same time, multijunction devices can be expected if wide-gap devices can be produced with performances comparable to the current generation narrow gap cells. Wide gap devices hold the direct potential for multijunction, one-sun photovoltaics with efficiencies exceeding 30% in modules and manufacturing costs below \$0.10/W. Current CdTe devices are limited by their heterojunction partner material, which absorbs significant light and generates no photocurrent. At the same time the back contact produces a Schottky barrier that reduces device output voltage and fill factor. These issues, when solved, should result in a doubling of module performance (24% modules are very possible) with a consequent reduction in cost per Watt of a factor of two. The Nanosolar CIGS technology features high-rate, low-cost ink-based printing, deposition on a flexible, low cost, low weight, and highly impermeable Al substrate. The major criticism of these technologies is raw material availability but no serious effort has been made to mine Te, and In is still produced as a byproduct of mining of other materials. Even a factor of ten increase in the price of these elements will leave the contribution to the final device no higher than for crystalline Si at current Si prices. Earth-abundant alternatives such as $CuZnSnSe_2$ and $CuAlSe_2$ are under investigation. Careful analysis shows excellent potential for reduction in balance of system costs for large arrays to fall in the range of \$1/W, making the cost of an installed system, less cost of capital and profit, under \$2/W. If one assumes that inflation in energy costs will offset the cost of capital, this would provide a levellized cost of electricity without further advances well under \$0.10/kWh. Expected advances outlined above would reduce this further such that chalcogenide solar cells would compete head-to-head with our lowest cost current energy technologies. There is no limit in sight for growth of these technologies. Even Si is worried.

“TITLE”

Prof. Harry Atwater
Materials Science
CalTech

ABSTRACT

“TITLE”

Dr. Subhendu Guha
Unisolar

ABSTRACT

Large Scale Arrays of Ultrathin, Microscale Solar Cells For High Performance, Unusual Format Photovoltaics

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Unconventional approaches to exploit monocrystalline silicon and other established materials in photovoltaics can create novel engineering opportunities, device functionalities, and cost structures, each with potential value in different applications. In this talk, I will give an overview of materials and fabrication strategies for photovoltaic systems that involve a large collection of ultrathin, microscale solar cells that are derived from bulk, wafer-based source materials through anisotropic wet chemical etching, epitaxial liftoff, and other processes. Techniques of deterministic assembly offered a practical means to manipulate ultrathin, microscale building blocks in a massively parallel manner, enabling device-level integration on various classes of foreign substrates with advantages in areal coverages, layouts, and costs that exceed possibilities with traditional, wafer-based technologies.

Characterizing and enhancing exciton harvesting in organic photovoltaic cells

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Organic semiconductors have received considerable attention for application in photovoltaic cells due to their compatibility with high-throughput processing techniques and lightweight, flexible substrates. In these systems, optical absorption leads to the formation of tightly bound electron-hole pairs known as excitons. Consequently, the generation of photocurrent in an organic photovoltaic cell (OPV) requires the use of a device architecture that permits the exciton be dissociated into its component charge carriers. Often, this is accomplished using a heterojunction between electron donating and accepting materials. In this scheme, photocurrent generation occurs only at the donor-acceptor (D-A) interface, and exciton diffusion to the interface is hence a critical step in the photoconversion process. Most organic semiconductors are characterized by exciton diffusion lengths that are considerably smaller than the optical absorption length. In an OPV, this trade-off between diffusion and absorption often necessitates the use of thin active layers to maximize exciton harvesting.

The focus of this talk will be on developing approaches that permit the accurate measurement of the exciton diffusion length, and realizing new device architectures that demonstrate enhanced exciton harvesting. In characterizing the exciton diffusion length, emphasis is placed on quantifying the role of D-A excitonic energy transfer in the dissociation process. Here, work to overcome the short diffusion length is focused on cells that rely on the use of either plasmonic nanostructures as a route to enhanced thin film optical absorption or, engineered D-A film morphologies that allow for enhanced exciton harvesting and high efficiency.

Polymer blend solar cells: Morphology Device Operation

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So-called organic bulk heterojunction solar cells rely on the blending of donor and acceptor materials to facilitate charge generation (splitting of excitons at donor/acceptor interfaces) and charge collection. The ideal morphology for optimising device performance is thought to consist of bi-continuous pure phases with domain size of around 10 nm, the exciton diffusion length. In practice the morphologies that are generated by the solution processing of blends is likely to deviate from this ideal case. A challenge for understanding the relationship between morphology and device performance in polymer blend solar cells is the difficulty in characterising blend structure on these length scales, having sensitivity to both local composition as well as interface structure. In this presentation I will overview the use of soft x-ray based techniques to probe the microstructure of polymer blend solar cells, focusing on polymer/polymer blends. The relationship between film structure and device performance will be discussed, as well as implications for polymer/fullerene solar cells.

Silicon nanostructures for next generation photovoltaics

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Engineered semiconductor nanostructures have the potential to revolutionize solar energy collection. Tunable, properties, low cost synthesis, new device architectures, and novel physics open the possibility of unprecedented increases in conversion efficiency at reduced cost. Silicon nanostructures are of particular interest because of silicon's high elemental abundance, low toxicity, history as a PV material, compatibility with mature silicon processing, and well understood doping mechanisms. At the same time, there are serious challenges to be overcome before these materials can achieve their potential. Controlling the defect structure of silicon nanocrystals is very important because silicon nanostructures tend to retain the indirect band structure and long lifetime of bulk material. Effective surface passivation is also essential because surface defects are less forgiving than, for example, with II-VI and IV-VI based nanomaterials. The requirements of charge collection place additional constraints on surface properties. This talk will provide a review of silicon nanostructures and their use in PV applications. Techniques for plasma synthesis of silicon quantum dots, nanoparticles, and nanowires will be discussed, along with the influence of bulk defects and methods of surface passivation. Evidence for hot carrier transfer in nanocrystalline Si, a mixture of Si nanocrystals in an amorphous matrix, will be given. Directions that silicon nanostructure photovoltaics can take in the future will be discussed. The research to be presented results from the work of a team of scientists within the NSF supported Renewable Energy Materials Research Science and Engineering Center at the Colorado School of Mines.

Probing Nanostructured Photovoltaics: Transport, Trapping, and Stability in Organic and Hybrid OPVs

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Disordered materials---from bulk heterojunction polymer blends, to thin films of inorganic colloids--play critical roles in many emerging solar cell technologies. This talk will describe the use of advanced electrical scanning probe methods such as time-resolved electrostatic force microscopy (trEFM) to characterize the effects of local heterogeneity in thin film solar cell performance, drawing examples from both organic and hybrid photovoltaics.

Contactless probing of nano-electronic materials and nanowire-based organic/inorganic hybrid solar cells

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Abstract: Nano-electronic materials such as nanoparticles, nanotubes, nanowires, nanobelts, etc. are intrinsically hetergenerous materials. The nanometer-scaled size of these materials make it extremely challenging to characterize

their electronic properties by using conventional methods such as four-probing transport measurements or Hall measurements. Furthermore, device performance is often dominated by the metal contact and thus rendering difficulties in probing the properties of the nanomaterials themselves. Here we present another variation of the scanning force microscopy technique : dielectric force microscopy (DFM), for contactless probing of nanoelectronic materials.The DFM technique measures the low-frequency dielectric response of nanomaterials by applying a voltage between a conducting AFM tip and the sample substrate, and senses the dielectric interaction force between the tip and the sample. Since low frequency dielectrics is directly related with materials conductivity in Drude model, the DFM technique can thus provide spatially resolved electronic property mapping of nanomaterials on a surface. We showcase the application of DFM by studying single-walled carbon nanotubes (SWNTs).

Another topic of the talk is nanowire-based hybrid solar cells. We investigate the photovoltaic conversion of the hybrid silicon nanowire array / PEDOT:PSS solar cell with radial photovoltaic junction and compare it with axial hetero-junction solar cells in order to understand advantages and disadvantages in the radial photovoltaic junction structure. The hybrid radial hetero-junction solar cells exhibit enhanced response for long wavelength sunlight due to improved separation efficiency of photogenerated carriers, resulting in increase in PEC by more than10 times over the hybrid axial hetero-junctions solar cells. By tuning the height of nanowire array, the external quantum efficiency and photovoltage decay measurements identify that inefficient charge collection due to high interfacial recombination and long charge collection path, especially in the top part of nanowires, limit the hybrid radial hetero-junction solar cell performance. We are currently investigating the structure-performance relationship of organic and/or hybrid PV devices using the DFM technique. This is also an open-end question for discussion at the talk.

References

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Challenges in Transparent Contacts for Thin Film Photovoltaics

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Transparent contacts based on heavily doped wide-gap semiconductors are critical components in a range of thin film photovoltaics. The challenge of providing high electrical conductivity while maintaining optical transparency across the absorption is daunting. However, the ability to tailor the transparent contacts to active layer in the PV system also offers some opportunities. In this presentation we discuss a range of oxide materials and the applicability in thin film PV technologies. Specifically we will discuss the design considerations of TCOs in CIGS and the Si based HIT cell geometry. These inorganic thin film technologies will be discussed in contrast to design consideration for organic thin film PV. Given these PV technologies efforts to create p-type transparent conducting materials will also be examined.

Novel Inorganic PV Materials

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Meeting future world energy demand, while strengthening energy security and avoiding the worst effects of climate change, will require the deployment of thousands of gigawatts of solar photovoltaic power generation. In order to keep manufacturing and deployment costs low, these panels will largely be made of thin film materials, but most thin film technologies today use toxic, rare, or expensive materials whose suitability decreases as the scale of manufacturing increases. Copper zinc tin suphide selenide solar cells have recently emerged as a promising candidate in the race for cheap, scalable, and environmentally benign thin film solar photovoltaics. This talk will discuss recent progress in the development and understanding of this kesterite system, as well as remaining challenges. Recent developments with other cheap, earth-abundant photovoltaic materials, specifically the recent report of depleted bulk heterojunction quantum dot solar cells, will be discussed as well, with a focus on their applicability to general thin film solar cell design and the creation of high efficiency, low-cost photovoltaics.

Organic-inorganic hybrids for optoelectronic devices

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Colloidal semiconductor nanocrystals (NCs) are solution processable semiconductors that are potentially highly appropriate for optoelectronic device fabrication, owing to their narrow bandwidth, their remarkably broad absorption spectrum obtained because of quantum confinement, their high dielectric constant, and their high stability under ambient conditions.

In spite of the interest drawn by this systems the results up to now have been disappointing. Most of the problems reside in the dichotomy between quantum confinement, and necessity of electronic wave function super-position to allow electrical transport. This problem is mostly related to the insulating nature of the organic ligands used to passivate and solubilize the NCs.

I will report about the strategies my group have been using to overcome these problems making NCs useful for optoelectronic applications. These strategies involve the use of organic molecules for the fabrication of functional interfaces between the NCs and the external world.

The physical phenomenon underlying the working mechanism of these hybrid organic-inorganic systems is either a long distance electron transfer between the inorganic NCs and organic molecules [ ] or tunnelling/hopping obtained by substituting the insulating ligands with functional linkers [ ]. Finally I will show that PbS NCs with benzene dithiols ligands can be use as active layer for efficient solar cells. Power conversion efficiencies approaching 4% and fill factors of 60% under AM1.5 illumination are obtained. The effect of different NCs` size on the performance and key parameters of the devices will be discussed together with peculiar features of the device functioning [ ].

Photo-induced charge transfer and chemical bond formation at dye sensitize TiO_2 interfaces

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An overview of dye sensitized solar cells will be presented. Photo-initiated charge transfer reactions that form iodine-iodine chemical bonds are important for the high efficiency in dye-sensitized solar cells yet the detailed mechanism(s) remain speculative. Here we will present mechanistic details for the creation and dissociation of I-I bond bonds. In addition, spectroelectrochemical measurements of sensitized thin films further indicate that injected electron influence the absorption spectra of surface bound sensitizers in a manner consistent with a Stark effect. The magnitude of the electric field is larger, 2.7 MV/cm. Transient Stark-like behavior occurs after iodide oxidation that is attributed to slow (μs to ms) screening of the surface electric field from the sensitizer. The influence of this field on I-I bond formation and breaking in dye sensitized solar cells will also be discussed.

Hot Electrons and Hot Plasmons for Photovoltaics

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We will discuss two recently observed phenomena with implications for photovoltaic devices. First, it is well known that conventional silicon solar cells lose a significant fraction of their absorbed energy when electrons that are excited high into the conduction band cool to the band edge. Although colloidal semiconductor nanocrystals (or quantum dots) had been proposed as a route to slow down this cooling so the excess energy of these hot electrons could be captured, no experiments had yet demonstrated this effect. We will describe recent experiments that show the first step of this process — extraction of hot electrons from PbSe quantum dots. Second, we will consider what happens when materials that are patterned on an optical length scale are heated. In this case, the pattern can modify the thermal emission of the material. This effect may lead to efficient thermophotovoltaic devices, which convert heat (from the sun or another source) into electricity. In this context, we will discuss the thermal emission of periodically structured metals. In particular, we examine simple metallic films with surfaces that are patterned with a series of circular concentric grooves (a bull's eye pattern). Due to thermal excitation of surface plasmons, a single beam of light can be emitted from these films in the normal direction that is amazingly narrow, both in terms of its spectrum and its angular divergence. Thus, metallic films can generate highly directional beams of light by a simple thermal process. Finally, we will discuss a general and simple route to fabricate such films that also has implications for other plasmonic approaches to solar cells.

Size Dependence of the Multiple Exciton Generation Rate in CdSe Quantum Dots

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Semiconductors typically produce a single electron-hole pair per photon absorbed. The excess photon energy is converted to heat and represents a net loss for the photoconversion efficiency. It is theoretically possible, however, for a photon of sufficiently high energy to generate two or more lower energy electron-hole pairs in a process known as multiple exciton generation (MEG). Provided that MEG occurs faster than competing carrier relaxation processes, more than one pair of charge carriers can be collected per photon absorbed. Thus, in addition to its fundamental physics interest, MEG raises the prospect of designing solar cell devices that utilize high energy photons with greater efficiency than is currently possible.

The multiplication rates of hot carriers in CdSe quantum dots are quantified using an atomistic pseudopotential approach and first-order perturbation theory. We consider both the case of an individual carrier (electron or hole) decaying into a trion and the case of an electron-hole pair decaying into a bi-exciton. The dependence on quantum dot volume of multiplication rate, density of final states, and effective Coulomb interaction are determined. We show that the multiplication rate of a photogenerated electron-hole pair decreases with dot size for a given absolute photon energy. However, if the photon energy is rescaled by the volume-dependent optical gap, then smaller dots exhibit an enhancement in carrier multiplication rate for a given relative photon energy. We find that holes have much higher multiplication rates than electrons of the same excess energy due to the larger density of final states (positive trions). When electron-hole pairs are generated by photon absorption, however, the net carrier multiplication rate is dominated by electrons because they have much higher excess energy on average. We also find, contrary to earlier studies, that the effective Coulomb coupling governing carrier multiplication is energy-dependent.

Quantum-confined nanocrystals as building blocks for next-generation photovoltaics

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In light of recent advances in synthesis, characterization, and the emerging understanding of their size-dependent properties, there are many exciting opportunities for semiconductor nanomaterials to contribute to the development of next-generation energy conversion technologies. Semiconductor nanocrystal quantum dots are particularly attractive material candidates for the efficient capture of solar emission in inexpensive, thin film photovoltaic devices due to their large absorption cross sections, low-cost solution-phase processing and size-tunable energy gaps. Despite the immense promise, the development of cost- and performance-competitive nanocrystal-based solar cells has, to date, fallen short of expectations. This gap is primarily due to the current lack of answers to the challenge of how to efficiently extract photogenerated charges from quantum confined systems and transport them to external electrodes. This talk will highlight recent progress in addressing these challenges. Major themes of the talk will include single- and multi-junction lead salt nanocrystal solar cells; the relationship between size-tuned energy levels and photovoltaic performance as well as processing/structure/property relationships underlying the assembly of nanocrystals in the active layer of the solar cell.