Energy Frontiers Focus Topic
Room: 15 - Session EN+NS-MoM

Nanostructured Solar Cells

Moderator: M.S. Arnold, University of Wisconsin Madison

8:20am **EN+NS-MoM1 Doping Control for the Development of Silicon Quantum Dot Solar Cell**, ***K.J. Kim***, *J.H. Park*, Korea Research Institute of Standards and Science (KRISS), Republic of Korea, *H.-J. Baek*, *H.H. Hwang*, University of Science and Technology (UST), Republic of Korea, *J.S. Jang*, Chungbuk National University (CBNU), Republic of Korea

Si quantum dots (QDs) imbedded in a SiO_2 matrix is a promising material for the next generation optoelectronic devices, such as solar cells and light emission diodes (LEDs). However, low conductivity of the Si quantum dot layer is a great hindrance for the performance of the Si QD-based optoelectronic devices. The effective doping of the Si QDs by semiconducting elements is one of the most important factors for the improvement of conductivity. High dielectric constant of the matrix material SiO_2 is an additional source of the low conductivity.

Active doping of B in Si nano structures and the effect of internal polycrystalline bridge layer were investigated by secondary ion mass spectroscopy (SIMS) depth profiling analyses. Phosphorous and boron doped-Si / SiO_2 multilayers on Si wafers were fabricated by ion beam sputtering deposition as a model structure for the study of the diffusion behavior of the dopants. The distributions of the dopants after annealing at high temperatures were analyzed by SIMS depth profiling analyses.

In this study, the diffusion behaviors of various dopants in silicon nanostructures will be discussed and the effects of the various parameters for the improvement of conversion efficiency in Si quantum dot solar cell will be introduced.

8:40am **EN+NS-MoM2 Photocarrier Generation in Si Quantum-dot Sensitized Solar Cells**, ***G. Uchida***, *H. Seo, Y. Wang, K. Kamataki, N. Itagaki, K. Koga, M. Shiratani*, Kyushu University, Japan

The pressing need for massively scalable carbon-free energy sources has focused attention on both increasing the efficiency and decreasing the cost of solar cells. Quantum-dot (QD) solar cells employing multiple exciton generation (MEG) have attracted much attention as a candidate for the third generation solar cells, because MEG represents a promising route to increased solar conversion efficiencies up to about 44 % in single junction. Our interest has been concerned with QD sensitized solar cells using Si nanoparticles [1]. The main purpose of this study is to discuss the characteristic of the quantum yield in view of the MEG effect.

QD thin films composed of size-controlled Si nanoparticles were deposited using double multi-hollow discharge plasma chemical vapour deposition (CVD) of a SiH_4/H_2 and CH_4 or N_2 gas mixture [2]. Short-circuit current density of Si QD sensitized solar cells increases by a factor of 2.5 by irradiation of CH_4 or N_2 plasma to Si nanoparticle surface. We also have measured incident photon-to-current conversion efficiency (IPCE) in the near-ultraviolet range using quartz-glass plates as front panels of QD sensitized solar cells. IPCE gradually increases by light irradiation in a wavelength range less than 600 nm around optical band-gap (E_g) of Si nanoparticle films, and then steeply increases below 280 nm around $2E_g$. This rapid increase of IPCE under the ultraviolet light incidence may be explained by the theoretically predicted MEG, the creation of two electron-hole pairs from one high-energy photon incidence, in Si nanoparticle QDs.

[1] G. Uchida, et al., Phys. Status Solidi C 8 (2011) 3021.

[2] G. Uchida, et al., Jpn. J. Appl. Phys. 51 (2011) 01AD01-1.

9:00am **EN+NS-MoM3 Quantum Dot Solar Cells with External Quantum Efficiency Exceeding 100% by Multiple Exciton Generation**, ***J.M. Luther***, *M.C. Beard, A.J. Nozik, O.E. Semonin*, National Renewable Energy Laboratory **INVITED**

Traditional semiconductors used in photovoltaic devices produce one electron from each absorbed photon. On the other hand, new materials such as quantum dots, nanorods, carbon nanotubes and graphene can more efficiently convert high-energy photons into multiple electron-hole pairs through a process titled multiple exciton generation (MEG) provided that the energy of the photon is at least twice the bandgap of the absorber. This process has been shown to be more efficient in highly confined quantum dots than other forms of carrier multiplication (such as impact ionization) in bulk materials. Photovoltaic devices can benefit greatly from MEG by producing increased photocurrent from the multiple electrons and thus allowing a single junction solar cell to yield a theoretical maximum efficiency as high as 44% compared to 33% for bulk semiconductors. In this talk, we will present recent findings from incorporating PbSe quantum dots (QDs) into semiconducting arrays that make up the absorber layer in prototype solar cells. In these devices, MEG is confirmed by demonstrating the first solar cell with external quantum efficiency (EQE) exceeding 100% for solar relevant photon energies. The EQE in our device reaches a maximum value of 114% at 380 nm and we have employed an optical model to determine that the PbSe QD layer produces as many as 1.3 electrons per photon (on average) for these photons. These findings are compared to ultrafast time resolved measurements of carrier quantum yields where we find reasonable agreement. We will also discuss future directions for materials designs that increase the quantum yield through more efficient MEG.

9:40am **EN+NS-MoM5 Quantum-Confined Nanocrystals as Building Blocks for Low-Cost Solution-Processed Multi-Junction Solar Cells**, *T. Hanrath*, ***J.W. Choi***, *W.N. Wenger, R.S. Hoffman*, Cornell University

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. The prospect of exploiting colloidal nanostructures for the creation of low-cost multi-junction solar cells has garnered immense scientific and technological interest. We recently demonstrated demonstrate solution-processed tandem solar cells created from nanocrystal quantum dots with size-tuned energy levels. Bringing this prospect to fruition requires the connection of absorber layers with cascaded energy gaps subject to stringent electrical and optical constraints. We show that interlayers composed of ZnO/Au/PEDOT provide appropriate carrier density and energy-level alignment to resolve this challenge. With such interlayers we have been able to create nanocrystal quantum dot tandem cells that exhibit IR sensitivity and a open circuit voltage approaching 1V. These advances provide guidelines for the design of an effective interlayer in tandem cell devices and suggest a promising future for solution-processed nanocrystal quantum dot solar cells.

10:00am **EN+NS-MoM6 Improvement of Carrier Transport in PbSe Quantum Dot-Embedded Polymeric Solar Cells Fabricated by a Laser Assisted Spray Process**, ***C. Hettiarachchi***, *D.M. Feliciano, D. Mukherjee, P. Mukherjee, S. Witanachchi*, University of South Florida

PbSe quantum dots (QD) in the size range of 4-8 nm are promising candidates for solar energy harvesting as they exhibit multi-exciton generation with ultraviolet (UV) photon absorption. While generation of multi-excitons has been demonstrated, dissociation of excitons to enhance current densities has not been realized. One of the main bottlenecks has been the difficulty in removing the surfactants on QDs to form a clear interface between the QD and the polymer matrix. We have developed a Laser Assisted Spray (LAS) deposition technique to deposit uniform coatings of surfactant-free QDs on substrates. This technique involves the transient heating of aerosols containing PbSe QDs by a CO_2 laser-gas interaction to burn the organic surfactants. Transmission electron micrographs and absorption spectroscopy show, under optimum conditions, the particles remain as single crystals and maintain quantum confinement. Growth parameters are optimized by monitoring the degree of surfactant removal by studying the Fourier Transform Infrared (FTIR) spectra of coatings grown by LAS technique. Two-layer solar cell structures of PbSe/polymer that is sandwiched between ITO and Al electrodes have been fabricated. Comparison of the IV characteristics of these cells and cells fabricated by PbSe QDs with ligand-exchange will be presented.

10:40am **EN+NS-MoM8 Single and Multiple Exciton Dissociation in Colloidal Nanoheterostructures**, ***T. Lian***, Emory University **INVITED**

The ability to control charge transfer dynamics to and from quantum dots (QDs) is essential to many QD-based devices, such as solar cells and light emitting diodes. Recent reports of multiple exciton generation (MEG) by one absorbed photon in some QDsoffer an exciting new approach to improve the efficiency of QD-based solar cells and to design novel multi-electron/hole photocatalysts. Two major challenges remain. First, the efficiency of MEG process needs to be significantly improved for practical applications. Second, the utilization of multi-excitons requires ultrafast exciton dissociation to compete with the exciton-exciton annihilation process, which occurs on the 10s to 100s ps time scale. In this presentation we report a series of studies of exciton dissociation dynamics in QDs and nanorods by electron transfer to adsorbed electron acceptors. We show that

excitons in CdX (X=S, Se, Te) and PbS QDs can be dissociated on the picosecond and and faster timescales and multiple excitons (generated by multiple photons) per QD can be dissociated by electron transfer to adsorbed acceptors. We discuss approaches for optimizing the single and multiple exciton dissociation efficiencies by controlling the spatial distributions of the electron and hole (i.e. wave-function engineering) in type II core/shell QDs and nanorods.

11:40am **EN+NS-MoM11 Intermediate Band Upconversion for Low-Cost, Solution Processed Photovoltaics**, ***J. Lewis***, *E.J.D. Klem, C.W. Gregory, G.B. Cunningham, S. Hall, D.S. Temple*, RTI International

PV devices based on disordered semiconductors such as polymers, organic small molecules, and colloidal quantum dots have seen gradually improving performance in recent years, but are likely to be limited to efficiencies in the range of 10–15%. To increase efficiency further would require the use of tandem cells, which adds complexity and cost. Alternatively one can pursue devices such as intermediate band solar photovoltaics (IBPV) that can exceed the Shockley-Queisser efficiency limit. In an IBPV device mid-gap states are incorporated into a wider band-gap host, allowing infrared photons to contribute to the photocurrent of the device via sequential absorption of two photons. Ideally this occurs without compromising the open circuit voltage. We will present the first example of an IBPV solar cell using solution processed, low-cost disordered materials. We show that the nature of the defect states in Pb-salt quantum dots is uniquely suited to efficient upconversion at optical power densities that are relevant for unconcentrated solar illumination. This demonstration provides a path for a step-change in the efficiency of low-cost PV.

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