Thursday Afternoon, October 22, 2015

Electronic Materials and Processing
Room: 211C - Session EM+EN-ThA

Materials for Light Management
Moderator: Michael Filler, Georgia Institute of Technology, Sang M. Han, University of New Mexico

2:20pm **EM+EN-ThA1 III-V Nanowires for Photonics and Solar Energy Applications**, ***Anna Fontcuberta i Morral***, EPFL, Switzerland **INVITED**

Semiconductor nanowires are filamentary crystals with a tailored diameter between few to few hundred nanometer. Their special shape and dimensions render them especially interesting for photonic applications. In my talk I will discuss several photonic applications of nanowires. I will start by showing how to modify light absorption and emission of nanowires by coupling them to plasmonic elements [1]. I will then follow by explaining the use of III-V nanowires for solar cell applications. I will show how, by choosing the adequate diameter and length, it is possible to obtain absorption cross-sections much larger than the nanowire physical size. This concentration effect can be used to increase the efficiency of nanowire-based solar cells and to reduce considerably the use of materials [2].

References

[1] A. Casadei et al , Scientific Reports 5, 7651 (2015)

[2] P. Krogstrup et al, Nature Photon. 7, 306 (2013) ; M. Heiss et al, Nanotech. 25, 014015 (2014)

3:00pm **EM+EN-ThA3 Formation of Wurtzite Phase by Si Doping and its Effect on the Optical Properties of GaAs Nanowires grown on Si Substrates by a Catalyst-free MBE-VLS Technique**, ***Marina Nakano***, *K. Sugihara, D. Ohori, K. Sakai*, Univ. of Miyazaki, Japan, *H. Amano, Y. Honda*, Univ. of Nagoya, Japan, *T. Ikari, A. Fukuyama*, Univ. of Miyazaki, Japan

GaAs nanowires (NWs) are expected to applying to optoelectronic devices. However, material properties have not been understood yet due to a presence of impurity and defect level related to an involved catalyst which was inevitable for growing nanowires. Recently, we succeeded in fabricating the catalyst-free GaAs NWs on a (111) Si substrates using a combination of molecular beam epitaxy and vapor-liquid-solid method [1]. The NW had two kinds of crystalline phases, a zinc-blend (ZB) and a wurtzite (WZ) structures [2]. We found the amount of WZ phase increased with increasing the amount of Si-doping by using high-resolution X-ray diffraction and transmission electron microscope [3]. In this study, we investigate the electronic band structure of Si-doped GaAs NWs by using a photoreflectance (PR) and a photoluminescence (PL) techniques and discuss the effect of Si-doping on the optical properties.

Three kinds of samples with different Si cell temperatures at 1015, 1065, and 1150ºC were grown. The average diameter and length of NWs were 60 nm and 35 mm, respectively. The amount of Si doping was evaluated by a carrier concentration estimated from a Hall measurement. The lowest hole concentration was 5.5×10^{17} cm^{-3} for the sample grown at 1015 ºc and increased about an order by increasing the cell temperature. PR and the PL emission light were carried at 4 K.

The crystallographic investigations showed that the amount of secondary WZ phase increased with increasing the Si-doping. Three critical energies were observed at 1.51, 1.49 and 1.43 Ev in the PR. The first two signals were observed for all samples and attributed to band to band and band to Si acceptor transitions, respectively. Since the signal at 1.43 Ev appeared only in high Si-doping sample with high amount of WZ phases, this is due to the band to band transition at the interface between the two different crystalline phases. In the PL spectra, three other emission peaks were observed at 1.46, 1.42 and 1.37eV. The intensities of these peaks changed for the samples with different cell temperature, these may be due to impurity and defect levels in nanowires. Si dopant itself as well as different crystal structure affect the electron transition. Since the interface transition observed at 1.43 Ev becomes dominant, emissions through such impurities were hidden for the sample with highest Si-doping. Temperature dependences of the PR and PL spectra will be discussed for further understanding the effect of Si-doping.

[1] J. H. Paek et al., Phys. Stat. Sol. (c) 6, 1436 (2009).

[2] D. Spirkoska et al., Phys. Rev. B 80, 245325 (2009).

[3] A. Suzuki et al., Jpn. J. Appl. Phys. 54, 035001 (2015).

3:20pm **EM+EN-ThA4 Nanowire Enabled 3-Dimensional Band Engineering for Efficient Next Generation Solar Cells**, ***Esther Alarcon Llado***, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, *O. Demichel*, Universite de Bourgogne, France, *A. Fonctuberta i Morral*, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland

Next generation photovoltaics (PV) aim to achieve large currents at high voltage by new materials and device concepts that overcome the main efficiency losses in traditional solar cells. Intermediate band solar cells (IBSCs) are a class of next generation PV where multi-energy levels in the semiconductor enable the scavenging of low energy photons and converting them into high voltage electrons. IBSCs have only been recently proven with highly mismatched alloys, however with very little efficiencies. The main challenge is the short lifetime of electrons at intermediate band states.

In this regard, the nanowire (NW) geometry offers potential advantages in the solar energy conversion process. Due to their richness in structure and morphology combined with doping and bandgap engineering, NWs provide an opportunity for new charge separation mechanisms.

In this work we propose a new IB-based solar cell design that is advantageously benefited from nanostructuring. We propose the use of core-shell heterostructures in order to reduce the optical coupling between the different band states in a three-level IBSC. Taking advantage of the intrinsic anisotropy of the nanowire geometry, the fundamental idea here is that excitons are separated by the heterostructure along the radial direction, while carrier extraction is performed along the axial direction. As a result, mid-gap recombination rate is reduced by several orders of magnitude.

On the other hand, it is known that optical resonances in NWs result into light self-concentrating effects that allow high absorption with reduced material. What's more, light resonances in NWs leave a very specific spatial distribution of light inside the nanostructure. By tuning the geometrical parameters of the NW, one can guide light around different regions in the NW depending on the photon energy. A combination of both electrical and morphological engineering, can lead to high efficiency PV.

4:00pm **EM+EN-ThA6 Effect of Internal Electric Field on the Miniband formation of Multi Quantum Well Solar Cell Structures Investigated by a Photoreflectance and a Photothermal Spectroscopy**, ***Tsubasa Nakamura***, *K. Matsuochi, T. Murakami, H. Suzuki*, University of Miyazaki, Japan, *K. Toprasertpong, M. Sugiyama, Y. Nakano*, The University of Tokyo, Japan, *T. Ikari, A. Fukuyama*, University of Miyazaki, Japan

Insertion of a multiple quantum-well (MQW) structure into the absorbing layer of solar cells is promising for accomplishing higher conversion efficiency. Recently, a MQW with a very thin barrier structure has been proposed to enhance the conversion efficiency [1]. The coupling of the wave functions between adjacent quantum wells causes a mini-Brillouin zone along the growth direction, which results in the formation of miniband. We have discussed carrier escaping mechanism in MQW by using photoreflectance (PR) and photothermal spectroscopy (PPT) and found that internal electric field in the QW region might affect the recombination probability [2]. In this study, we investigate the effect of internal electric filed on the miniband width.

Three kinds of MQW samples were grown by a metal-organic vapor phase epitaxy technique. Two GaAs p-i-n solar cell structure samples with MQWs in the i-layer were prepared. The doping levels in the p- and n-type layer were changed and this induced the different strength of the electric field in the absorbing layer. Another sample had GaAs n-n structures without any electric field in the absorbing layer. The thicknesses of the well barrier were changed from 2 to 6 nm for discussing the detailed miniband formation. PR and PPT measurements were carried out at room temperature. The miniband width was estimated from the difference of the peak energies of the PR modulus spectra. The lower and higher energy peak correspond to the energies of bottom and top of the miniband, respectively. The PPT method is used to detect the heat generated by non-radiative recombination of photo generated carriers. The miniband width was also calculated from the Gaussian decomposition technique of the observed PPT spectra [3].

Decrease of the miniband width by increasing the barrier width was observed for all samples. This is coincide with the theoretical prediction. The miniband width for n-n structure is considered to be larger than that of p-i-n structure. Applied electric filled may reduce the wave function overlapping between the adjacent wells. The increase of the miniband width by the electric field for the p-i-n structure sample was observed. However, the increase of the miniband widths for n-n structure could not be confirmed from the PR spectra. Since the PPT measurement is more sensitive for estimating the band edge transition, effect of the electric field may be more clearly observed by comparing the PR and PL spectra.

[1] Y. Wang, et al., J. Cryst. Growth 352, 194 (2012).

[2] T. Aihara et al., J. Appl. Phys. 116, 044509 (2014).

[3] T. Aihara et al., J. Appl. Phys. 117, 084307 (2015).

4:20pm **EM+EN-ThA7 Controlling Light Absorption with Nanophotonics**, ***Vivian Ferry***, University of Minnesota **INVITED**

Luminescent solar concentrators (LSCs) offer many advantages over traditional concentrator geometries. As opposed to concentrators that rely on tracking, LSCs operate under both direct and diffuse illumination and require the solar cell to only be efficient at a small range of wavelengths. In practice, most LSCs suffer losses from reabsorption of emitted light, non-unity quantum yields, and incomplete light guiding to the solar cell. Here we combine tunable lumophores based on quantum dot heterostructures with photonic designs to improve the concentration efficiency of LSCs and study light propagation within the device.

To achieve high concentration ratios it is critical to have high effective Stokes shifts, high quantum yields, and to reduce escape cone losses. We synthesized a series of core-shell nanocrystal lumophores that exhibit tunable emission. We show how the narrow emission bandwidth of these nanocrystals enables the use of a 1D photonic mirror on the top surface of the device, designed to admit incident sunlight and trap luminesced light from the nanocrystal. In combination, the concentration ratios from these devices exceed the performance of dyes with higher quantum yields but broader emission. Another approach to photonic LSCs is to restrict the angle of emission from the lumophores to promote coupling to the total internal reflection modes of the LSC. This talk will discuss designs for the latter approach and compare achievable concentration factors.

The second portion of the talk will discuss light management strategies for solid-state lighting, and the incorporation of plasmonic nanostructures to enhance light outcoupling from solid-state devices. This section of the talk will compare and contrast plasmonic structures for solar cells and solid-state lighting, and discuss ways that design rules should be adjusted for different materials systems.

5:20pm **EM+EN-ThA10 Symmetry-Breaking in Periodic Nanostructures for Enhanced Light Trapping in Organic Solar Cells**, ***Seok Jun Han***, *S. Ghosh, O.K. Abudayyeh, E.J. Martin, J.K. Grey, S.M. Han, S.E. Han*, University of New Mexico

In this study, we introduce a new light-trapping scheme for organic solar cells by systematically breaking the symmetry in periodic nanostructures on the bottom metal contact. To create symmetry-breaking metal nanostructures, we start by fabricating a mold from a crystalline silicon (c-Si) substrate. We intentionally misalign the etch mask with respect to [110] crystallographic orientation of the c-Si. Subsequently, silver is sputter-coated over the nanoscale recess created in the c-Si substrate to create the metal nanostructures, and an organic photoactive material, PCPDTBT, is spin-coated on the silver layer. The enhancement in light absorption is achieved at surface plasmon resonances at the polymer-metal interface. We demonstrate that surface plasmon band structure can be tailored by symmetry-breaking. In experiment, we increase the number of surface plasmon bands in the visible spectrum and locate the bands at the desired wavelengths by controlling the symmetry. In general, by patterning a flat film in symmetry-breaking structures, absorption is enhanced from 65% to 85% in a broad short wavelength spectrum. Moreover, the absorption spectrum is extended into long wavelengths by 20 nm. We expect that our low-cost, symmetry-breaking fabrication strategy would be scalable and lead to a manufacturable process for efficient light-trapping in organic photovoltaic devices.

5:40pm **EM+EN-ThA11 Symmetry-Breaking in Light-Trapping Nanostructures on Silicon**, ***Sang Eon Han***, *S.J. Han, S. Ghosh, T. Cai, B. Hoard, S.M. Han*, University of New Mexico

In thin-film photovoltaics, highly absorptive materials are conventionally used. However, these materials have achieved efficiencies that are not comparable to those of thick crystalline silicon (c-Si) photovoltaics and, in some cases, suffer from their toxicity and low supply. A viable solution to these problems would be to use c-Si for thin-film photovoltaics. However, thin c-Si films absorb sunlight weakly because of its indirect band gap and strong light-trapping should be provided to achieve high efficiency. For thin-film photovoltaics, nanoscale structures are typically involved for light trapping because the film thickness becomes comparable to the wavelength of sun light. While diverse nanostructures have been studied to break the light-trapping limit of geometric optics, known as the Lambertian limit, highly efficient nanostructures that can be easily manufactured have not been demonstrated. We have previously predicted that symmetry-breaking in light-trapping periodic nanostructures on thin films can approach the Lambertian limit very closely. Herein, we will present how the systematic symmetry-lowering increases light-trapping in c-Si thin-film photovoltaics. We will demonstrate the experimental realization of such low-symmetry structures using simple wet etching methods on c-Si(100) wafers without any off-cut, tilt angle. Further, we will discuss the optical characterization of our fabricated structures on thin c-Si films.

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