Electronic Materials and Processing
Room: 311 - Session EM1-ThM

Materials for Light Management

Moderator: Sang M. Han, University of New Mexico

8:40am **EM1-ThM3 Thin Film c-Si Solar Cells – Detailed Understanding from Light Trapping to Carriers Collection**, *M.S. Branham, W.-C. Hsu,* Massachusetts Institute of Technology, *S. Yerci,* Middle East Technical University, Turkey, ***Gang Chen***, Massachusetts Institute of Technology **INVITED**

Crystalline silicon (c-Si) is the dominant material in photovoltaic industry. However, it contributes ~40% of the total module cost of c-Si solar cells, and a thin-film device has been one strategy to reduce the usage of material. Here, we demonstrate experimentally that an inverted nanopyramid light-trapping scheme for a 10μm-thick c-Si thin-film solar cell can achieve an absorptance value comparable to that of a 300μm-thick planar device and its efficiency higher than 13%. To reach the high efficiencies necessary for a commercial product, we constructed a multi-physics optimization tool incorporating both optical absorption and electronic carrier collection to understand in detail loss mechanisms including incomplete photonic absorption, contact losses, surface, Schottky-Read-Hall and Auger recombination. Our model predicts that a 10μm-thick thin-film c-Si solar cell with an inter-digitated back contact scheme can have an efficiency higher than 20%. Finally, we calculated the optimum height to period ratio of light-trapping structures around 0.7 for a fixed period of 700nm. This structure can be obtained in crystalline silicon using a well-known potassium hydroxide anisotropic etching. These multi-physics simulation results can provide design insights for flexible and high efficiency thin silicon solar cells.

9:20am **EM1-ThM5 Symmetry-Breaking in Light Trapping Nanostructures on Silicon for Solar Photovoltaics**, ***SangEon Han***, *S. Ghosh, T. Cai, B.R. Hoard, S.M. Han*, University of New Mexico

In thin-film photovoltaics, highly absorptive materials are conventionally used. However, these materials except gallium arsenide 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 highly efficient 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 thin-film photovoltaics. Further, 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.

9:40am **EM1-ThM6 Suppressing Optical Absorption in Nanostructured Metal Electrodes in Photovoltaics**, ***Samuel Clark***, *S.E. Han*, University of New Mexico

Electrodes are ubiquitously used in optoelectronic devices such as solar cells, infrared detectors, and light emitting diodes. Typically, metals exhibit good electrical conductivity due to their free electrons and are suitable for electrodes in these devices. However, metal electrodes cause inefficiency in the devices by absorbing light as their free electrons suffer from collisions. To circumvent this problem, nanostructured metals are being explored to realize low optical losses while maintaining large electrical conductivity. Here, we study optical absorption in helical metal nanocoils and find that absorption can be dramatically decreased when the metal is suitably nanostructured. Theoretical modeling showed that this effect is due to the increase in effective mass of free electrons in nanostructured metals. Heavy electrons suffer a decreased rate of collision and emulate dielectric materials where optical losses are negligible. Calculations showed that, when metal electrodes are used in semiconductor devices, suitably chosen nanostructures can increase the fractional absorption in semiconductors more than 60 times by reducing losses in the metal. Further, we show that a two-dimensional analogue to nanocoil, namely serpentine structure, exhibits optical losses of less than 7 % in the infrared even at a large metal area fraction of 0.3. We will discuss the different physics of optical losses between the coil and the serpentine structures.

11:00am **EM1-ThM10 High Efficiency Si Cells and the Challenges to Integrate the Light Management**, ***Paul Stradins***, *B.G. Lee*, National Renewable Energy Laboratory **INVITED**

In this talk, we discuss the stringent requirements that enable the high efficiency, industrially relevant, Si solar cells, and show that the light management approaches need to be developed integral to the whole device. The highest efficiencies known today are obtained with PERL (UNSW), IBC (SunPower) and IBC Heterojunction (Panasonic) device architectures. The challenge is to balance the excellent bulk, surface, and contact passivation leading to high Voc, with light management features leading to high Jsc. For example, pyramid-texturing the front of the cell leads to an excellent visible range response and near-Lambertian light trapping in near-infrared, but the associated 1.7x increase in the front surface area increases the recombination current prefactor. The IBC approaches significantly restrict any light management structures on the back of the cell (e.g. plasmonics, gratings). Novel passivated contact approaches currently pursued by NREL [1] and others [2] show promise to significantly enhance cell efficiencies in an industrially relevant way. In particular, we have developed [1] high performance tunneling passivated full area back contact for the n-CZ based cell. Because of the high-low junction induced by a deposited n+ poly-Si contact layer, there is no P-doping involved in BSF formation. The contact itself provides better BSF passivation than currently used nitride-passivated BSF surface, has low contact resistance, and does not need patterning as in PERT or PERL structures. We then discuss of how advanced optics and light trapping can fit into this device architecture and are there viable alternatives to the near-Lambertian pyramid texturing. With near-perfect bulk and surface/contact passivation, the importance of light management increases. However, it becomes increasingly more challenging to justify much thinner wafer cells even with perfect Lambertian light trapping. For high efficiency, passivated contact wafer cells, additive light management structures provide potential efficiency improvements and will be discussed. Finally, we will briefly discuss numerous light management approaches examined in the course of our previous Si program that focused on <10 micron thin c-Si devices (small pyramids, black Si, dielectric nanoparticle backscatterers), and their potential to high efficiency Si cells.

1.D. L. Young et al., SiliconPV conference proceedings 2014.

2.F. Feldmann et al, Sol. En. Mat. Sol. Cells (2014) 120, pp. 270-274.

11:40am **EM1-ThM12 Developing Periodically Oriented Gallium Nitride for Frequency Conversion**, ***Jennifer Hite***, *R. Goswami, J.A. Freitas, Jr., M.A. Mastro, I. Vurgaftman, J.R. Meyer,* U.S. Naval Research Laboratory, *C.G. Brown,* Sotera Defense Solutions, *S.R. Bowman, C.R. Eddy*, U.S. Naval Research Laboratory

Gallium nitride is a semiconductor widely used in both optical and electronic devices. The polarity of GaN (+/- c-direction) influences many properties of the resultant material, including chemical reactivity and electric field in these 'spontaneously polarized' materials. By engineering inversion layers, we have demonstrated control of GaN polarity on both polar faces of GaN. By employing a selective growth method to deposit the IL, the lateral polarity of the GaN can be alternated, thus enabling structures referred to as periodically oriented (PO) GaN.

In previous work on N-polar substrates, we demonstrated that optimization of the MOCVD growth rates resulted in sharp, vertical interfaces and smooth surfaces. The present work has moved the technology substantially closer to practical non-linear optic emitters by using HVPE to extend the PO GaN templates on N-polar substrates to total thicknesses of up to 80 μm, while faithfully maintaining the pattern of alternating polarity. Additionally, cross-sectional cathode-luminescence (CL) imaging of such an extension shows that the large initial dislocation densities occurring in the original inversion layers greatly decreased after about 25 μm of regrowth.

For growth on Ga-polar substrates, we have demonstrated that inversion layers can be created using atomic layer deposition (ALD) of Al_2O_3. This new capability is especially relevant because Ga-polar films are more prominent in devices, as they result in lower impurities, higher quality and smoother films. In this case, GaN grown over the inversion layer is N-polar. This inversion layer was used to form laterally-patterned stripes of alternating Ga- and N-polar films. We find that annealing the ALD films crystallizes the Al_2O_3, thereby allowing N-polar GaN to be grown over the new sapphire-like surface. Transmission electron microscopy shows that the inversion layer in a PO GaN structure is crystalline, a-plane oriented, and a-phase. TEM characterization further indicates that the GaN layers, both above and below the Al_2O_3 inversion layer, are c-oriented without any

rotation between them. The optimization of this process has enhanced the surface smoothness.

These methods of GaN polarity inversion offer the promise of engineered materials with custom lateral and vertical polarity variations for applications in novel electronic and optoelectronic devices, a subset of which are expected to be suitable for non-linear optics.

12:00pm **EM1-ThM13 White-Light Emission from Amorphous ZrHfO/ AlO_x/ZrHfO high-*k* Stack**, *C.-C. Lin,* ***Yue Kuo,*** Texas A&M University*, X. Zhang*, Xi'an Jiaotong University, China

LEDs has the low energy consumption, compact size, and long-lifetime [1]. Since the white light cannot be emitted from a single LED, a combination of red, green, and blue LEDs or an UV or blue LED with a yellow phosphor has to be used. Kuo and Lin proposed a new type of single-chip, white-light emission LED that is made of the amorphous high-*k* dielectric thin film on a Si wafer [2-5]. The light emission is from the thermal excitation of nano-size conductive paths formed during the dielectric breakdown, which is similar to the principle of the incandescent device. Its energy efficiency is expected to be much higher than that of the incandescent light bulb because of the small size conductive path. The emission light intensity and wavelength range of the LED were enhanced with the embedding of a nanocrystal layer in the high-*k* film paths [2]. Authors investigated optical and electrical characteristics of the ZrHfO/AlO_x/ZrHfO LED.

The following results were obtained from this study. First, the AlO_x embedded ZrHfO LED emits the broad band light including the visible to near IR wavelengths. Second, the emitted light falls into the warm white light region of the CIE 1931 color chart with a high color rendering index (CRI) of ~98. Third, the LED has a larger leakage current than the control sample, i.e., ZrHfO without the embedded AlO_x layer, which is due to the stress mismatch between these two materials film [6]. Fourth, both the emission light intensity and the number of the bright dots increase with the inclusion of the AlO_x layer and the increase of the magnitude of the stress voltage ($|V_g|$). These phenomena can be explained by the mechanism of thermal excitation of the conductive path. The large current density causes the high thermal excitation efficiency of the conductive path for the high intensity light emission. The larger number of conductive paths also contribute to the high emission intensity. Fifth, light emission was studied with the pulsed V_g driving method, i.e., at 1 kHz and -40 V, at various duty cycles (DCs). The spectrum wavelength range was independent of the change of DC. However, the peak height decreases with the decrease of the DC. It can be explained by the fast thermal excitation process of the extremely short conductive path, i.e., ~8.7 nm. The new LED can be an important white light source for many industrial, medical, etc. applications.

[1] N. Kimura, APL 90 051109 (2007)

[2] Y. Kuo et al., APL 102, 031117 (2013).

[3] Y. Kuo et al., Electrochem. Solid-State Lett. 2, Q59 (2013).

[4] Y. Kuo et al., Solid-State Electron. 89, 120 (2013).

[5] C. -C. Lin et al, JVSTB 32, 011208 (2014).

[6] C. -C. Lin et al, JVSTB 32, 03D116 (2014).

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