Toward high-efficiency thin film solar cells combining multi-junctions and nano-scale light management

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Abstract

We have achieved significant accomplishments on the developing of high-efficiency thin film multi-junction solar cell with nano-scale light management. The highlights include:

(1) Developed a computational tool for the detailed balance analysis of nanophotonic structures showing that absorption in a solar cell at all angles is sufficient to calculate and understand the fundamental behavior of nanophotonic solar cells.
(2) Elucidated the physics of open-circuit voltage enhancement by analyzing the angular and spectral distribution of the cell's absorption spectrum.
(3) Demonstrated a novel nano-window GaAs Solar cell that achieved 17% efficiency, and highest V_{oc} (~1V) in nanostructure solar cell.
(4) Demonstrated equaivalent apbsorption in a160 nm free-standing nano-structured GaAs thin film absorber to that of a 1μm thick planar cell. The absorption of this nanopyramid structure is as twice as much that of a planar structure with same thickness and equivalent to a planar structure with 1 μm thickness.
(5) Successfully developed a new etching technique which produces the first batch of working thin film GaAs cells.
(6) Successfully developed the process for generating large area free-standing thin-film single-crystalline Si down to 2μm thickness.
(7) We are developing a model system to realize super scatterers and test their light trapping properties on an SOI detector test platform, which can accurately quantify the light trapping ability of model scatters. We have demonstrated the light trapping ability of Si nanowires on the platform and are now designing metal coated nanowire superscatterers and absorbers.

Introduction

In this project, we will specifically address development of practical ultra-thin single crystalline GaAs, AlGaAs and c-Si solar cell structures, as well as AlGaAs/c-Si tandem cells. While GaAs solar cells now have the highest conversion efficiency for single-junction cells, their widespread application has thus far been limited by the high material

cost of GaAs. Cost reduction of cells has been the enabler for the current rapid increased installation of c-Si and thin film solar cells. However, for c-Si and traditional thin film cells, cell cost is no longer the major cost for installed solar arrays and thus not the driving limitation to larger markets. Higher efficiency is now becoming the game changer for solar cells because efficiency affects all aspects of the system, including cell cost, module assembly cost, real estate area, installation and maintenance. Our approach is designed to significantly increase solar cell array efficiency, while minimizing cost increases by developing very thin cell structures as enabled by nanostructures and light management. This approach may ultimately enable the use of thin-film AlGaAs/c-Si tandem cells where the overall installed system cost for the system can be reduced by the increased efficiency of the cell. There are a number of fundamental challenges to demonstrate the significant improvement in efficiency as outlined below:

Light management over the entire broad solar spectrum with optimum division for current matching in multi-junction cells. Much of the work on nanophotonic structures has focused on absorption enhancement and light guiding over narrow bandwidths for optical communications and in homogeneous media, but these are inherently unsuitable for solar applications and particularly for multi-junction cells where both spectral and spatial distribution of photon absorption are critical.

Nanostructured solar cell architecture design for high efficiency solar cells. Most of the techniques previously applied to create nanophotonic structures and trap light create excessive surface damage that drastically degrades the electronic properties of the active layers. This typically results in a deterioration of the fill factor in the current voltage relation, as well as a lowering of the open-circuit voltage.

Realize low-cost, high performance, ultra-thin layer multi-junction solar cells. We propose an approach which is fundamentally based upon c-Si, but not constrained by lattice match of a second cell to be wafer bonded and produce a revolutionary single crystal thin-film cell. The challenges will be to develop individually high-performance cells that incorporate designer photonic nanostructures for precise spectral and spatial light management and carrier trapping to increase Voc and efficiency, and develop wafer bonding techniques that minimize absorption at the thin layer interface.

Progress

In recent years, nanophotonic structures have been extensively explored for light management purposes for solar cell applications. To fully realize the potential of nanophotonic structures for applications in solar cells, however, there are a number of significant challenges that still need to be addressed. In particular, there is a critical need to develop a strategy for enhancing light absorption over the entire solar spectrum in order to use ultra-thin active layers. Also, one needs to optimize both the optical and the electronic properties of the nanophotonic solar cells. Our research directly targets these fundamental challenges and will represent a significant step forward compared with the current state-of-the-art. In this project, we will also apply the nanophotonic concepts specifically towards the developments of practical ultra-thin GaAs solar cell structures, as well as Si/GaAs tandem cells. Through nanostructuring and thin-film liftoff, we aim to

bond ultra-thin films to low-cost substrates, and produce a cell with not only lower cell cost, but one which can reduce module cost and achieve >32% efficiency—more than double the efficiency of today's thin film and 50% over c-Si solar cells. Such a cell would radically change the landscape for large-scale introduction of photovoltaic systems to provide both new generating capacity and replace aging capacity in the already industrialized world.

There is very strong recent interest in nanophotonic solar cells as a way to improve solar cell efficiency and reduce cost[1] [2]. Most of the previous analysis has only focused on calculating the absorption properties of the device in order to determine its current characteristics[3] [4] [5] [6] [7] [8] [9] [10] [11]. However, to obtain the limiting performance of these nanophotonic solar cells, one needs to understand the thermodynamic constraints on both its voltage and its current.

Nanostructure solar cell modeling

To understand these constraints on current and voltage, a detailed balance analysis[12] [13] [14] [15] needs to be carried out on the nanophotonic solar cell. In our recent work[16], we provided the first such detailed balance analysis of structured nanophotonic solar cells. We showed that the absorption spectrum of a solar cell at all angles, as one routinely calculates in solar cell optical modeling, is in fact sufficient to calculate and understand the fundamental behavior of nanophotonic solar cells from the aspects of both its current and its voltage. Moreover, our approach can be readily generalized to include intrinsic material non-idealities. Using this tool, we elucidated the physics of voltage enhancement in nanophotonic structures, and we showed that the voltage and the current are controlled by different parts of the absorption spectrum and, hence, can be separately optimized.

In the following, we compare the results of our detailed-balance analysis for the following GaAs solar cells: (a) a 10 um thick bulk structure with multi-layer anti-reflection coating on its front surface [Figure 1(a)], (b) a 43.8 nm thick thin film [Figure 1(b)], and (c) a GaAs grating structure with an effective thickness of 43.8nm [Figure

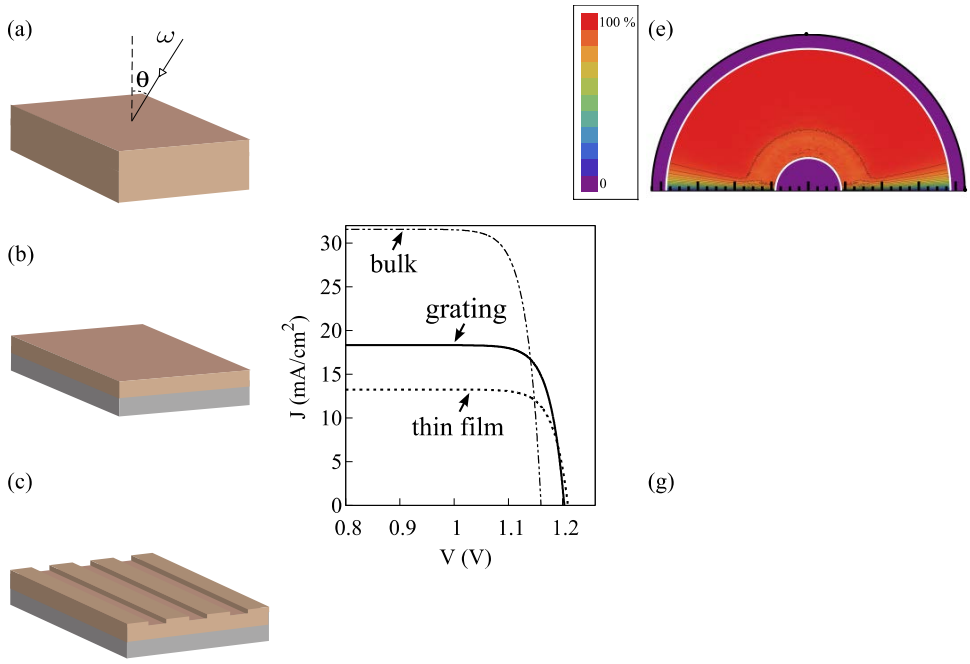

Figure 1: (a) – (c) shows the three GaAs structures compared int his report: (a) 10um thick GaAs bulk structure with multi-layer anti-reflection coating, (b) 43.8nm thick GaAs thin film (gold color), and (c) GaAs grating nanostructure (gold color) with an effective thickness of 43.8 nm [The definition of effective thickness here is such that the grating structure has the same amount of absorbing material as the thin film in (b)]. Both structures in (a) and (b) have a perfect reflecting back surface (grey color). Also shown in (a) is the propagation direction of an incident plane wave with frequency , and polar angle . (d) shows the current (J) – voltage (V) curves for the structures in (a) - (c). (d) - (g) shows the contour-density plots of absorptivity spectra for different polar angles θ of: (d) the bulk GaAs structure in (a), (f) the thin film structure in (b), and (g) the grating structure (c). The plot in (g) includes an integration over all azimuthal angles for each polar angle θ. The absorptivity in (d)-(g) is the mean absorptivity of the transverse electric and transverse magnetic incident polarizations.

1(c)]. Both the nanostructures in Figure 1(a)-(b) have a perfect back reflector. In order to establish an upper-bound in the solar cell's performance, we idealize to the case of a defect free GaAs cell with perfect surface passivation. Under these conditions, the only important non-radiative mechanism in our detailed-balance analysis is Auger-recombination[17 18]. Although we do include Auger-recombination in the following calculations, we note that for the GaAs cells considered in this report, this Auger-recombination rate is very small as compared to the cell's radiative recombination rate. Therefore, the open-circuit voltage for these cells is approximately logarithmically proportional to the ratio of the cell's generation rate and its thermal equilibrium recombination rate[19].

The dashed and dotted lines in Figure 1(d) compares the current (J) – voltage (V) relationship of the bulk cell [Figure 1(a)] and the thin film [Figure 1(b)], respectively. The use of the thin film results in an open-circuit voltage of 1.21V, which is significantly higher than the 1.16V open-circuit voltage of the bulk structure. This result indicates a very important potential of nanoscale thin film structures to boost solar cell performance. However, Figure 1(d) also shows that the short-circuit current of the thin film in Figure 1

(b) suffers significantly relative to that of the bulk cell. One natural approach to enhance the short-circuit current of the thin film would be to introduce light trapping[20], for example the optimized grating structure shown in Figure 1(c). The solid line in Figure 1(d) shows the J-V curve of this grating structure. We see a large enhancement of its short-circuit current relative to that of the thin film. In addition, the open-circuit circuit voltage of the grating structure is maintained at approximately the same enhanced value as that of the thin film.

In order to elucidate the physics of open-voltage enhancement, we examine the thermal emission properties of all three structures in Figure 1(a)-(c). Figure 1(e)-(g) shows the absorptivity spectra as a function of polar angle associated with the three structures in Figure 1(a)-(c), respectively. We notice that the bulk cell [Figure 1(e)] has ~100% absorption for almost all polar angles and wavelengths up to the GaAs band edge. This strong absorption of the bulk cell results in a very strong radiative generation rate (Fs) and, consequently, a large short-circuit current. However, this strong absorption also results in a very strong thermal equilibrium recombination rate (F_{co}) i.e. dark current. Consequently, since the open-circuit voltage of the GaAs cells is approximately logarithmically proportional the ratio of F_s and F_{co}, the low contrast between F_s and F_{co} of the bulk cell results in a open-circuit voltage that is significantly lower than the nanostructures [Figure 1(d)].

On the other hand, in the case of the thin film [Figure 1(f)], we notice that there is strong absorption suppression over the immediate frequency range above the bandedge. This absorption suppression frequency range has a width corresponding to the thermal emission spectrum width of the cell and, therefore, has a strong influence on suppressing the cell's thermal equilibrium recombination rate (F_{co}). On the other hand, this absorption suppression width corresponds to a small fraction of the total absorption bandwidth of the cell. Moreover, since the solar radiation bandwidth is much wider, reducing the absorption in the immediate vicinity above the bandedge has much less influence on the cell's radiative generation rate (F_s). Therefore, this absorption suppression in the immediately region above the bandedge leads to an increased contrast between F_s and F_{co}, and, consequently, leads to an enhancement of the thin film's open-circuit voltage over that of the bulk cell associated with Figure 1(e).

In the case of the thin film absorptivity spectra [Figure 1(f)], a strong reduction in absorption at the normal angle $\theta=0$ over the entire frequency range above the bandedge also leads to a significant reduction of its short-circuit current relative to the bulk cell associated with Figure 1(e). However, as illustrated in the previous paragraph, the open-circuit voltage and short-circuit current are really controlled by different parts of the absorptivity spectra. Therefore we design the grating structure in Fig. 1g, which suppresses absorption and hence thermal radiation immediately above the bandedge, and in the mean time enhances the short-circuit current over the broad solar spectrum. This results in the enhancement of the both the short-circuit current and the open circuit-voltage.

Nanostructure solar cells

Nanostructures have been widely applied to solar cells for antireflection coatings[21], light trapping absorbers[22,23], core-shell radial p-n junctions[24], back reflectors[25], etc. Most of these devices have demonstrated enhanced short circuit current density (J_{sc}) due to advanced antireflection and light trapping effects. However, nanostructures also increase the surface area and the number of defects, which results in lower open circuit voltage (V_{oc}), fill factor (FF) and efficiency. In spite of quite major efforts to solve these problems[2, 3, 4], they remain significant challenges to utilizing nanostructures to achieve higher efficiency. In a solar cell with nanostructured junctions,[26] without considering the parasitic resistance, V_{oc} can be expressed as

$$V_{oc} = \frac{m\,k_B T}{q} \ln\left[\left(\frac{J_{sc}}{J_0\,\Gamma}\right) + 1\right] \quad (1)$$

where m is the ideal factor that is close to 1 for a good diode, J_0 is the dark saturation current density, and Γ is the area of the junction in the cylindrical geometry relative to the area of the cylinder base area. Planar structured solar cells have $\Gamma = 1$. High aspect ratio nanowire solar cell with radial p-n junctions have Γ that is significantly larger, thus lowering the V_{oc}. In addition to the junction area, higher quality junctions from material with long lifetime and diffusion length lead to lower saturation current, J_0, which also leads to higher $V_{oc.}$ For conventional radial p-n junction nanostructured solar cells, the lifetime and diffusion length can be seriously degraded by increased defects if the junction is grown on a nanostructured template. It can also be limited by the radial layer thickness of the wire structure. Though a radial junction does not require long lifetime and high diffusion length to collect carriers and achieve high photocurrent, the reduced lifetime and diffusion length do affect V_{oc}. This drawback is more significant in single crystalline materials with long diffusion lengths, such as GaAs, compared to polycrystalline or amorphous materials. Therefore, novel nanostructured solar cell architecture is desired. Here we demonstrate a nano-window solar cell design with nano-cone shape AlGaAs window layer fabricated on top of planar GaAs p-n junction, such that the electronic properties of the GaAs p-n junction are preserved.

GaAs epitaxial lift-off techniques

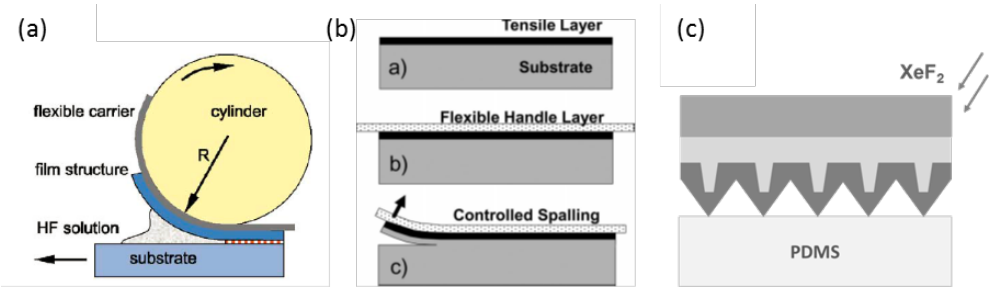

Figure 2. (a) A lift-off process to release GaAs solar cell layer by chemical etching.[7] (b) Scheme of Controlled spalling process.[8] (c) GaAs-Ge core-shell nanopyramids attached to PDMS superstrate in XeF_2 gas etching.[9]

Recently, several epitaxial lift-off techniques to fabricate thin-film GaAs solar cells and to reuse the GaAs substrate have been developed. A large-scale process has been developed by Alta Solar, providing an existence proof that a large-scale liftoff process in

possible. A well-established approach is that depositing an AlGaAs sacrificial layer onto the GaAs substrate prior to growth of the GaAs solar cell layers, followed by a chemical etch to selectively etch the AlGaAs layer and to release the solar cell layers from the substrate (Fig. 2a).[27] Alternatively, a controlled spalling technique is demonstrated by Bedell, *et. al* to peel off the III-V material from Ge substrate, which requires a stressor layer to be deposited on the surface, and the controlled removal of a continuous surface layer could be performed at a predetermined depth by manipulating the thickness and stress of the stressor layer (Fig. 2b).[28] Another mechanism developed in Harris lab involves growth of a Ge layer as the sacrificial layer, followed by a XeF2 gas etchant that selectively removes the Ge layer without affecting the GaAs cell (Fig. 2c).[29] These approaches have been previously used in small-area GaAs based devices. In this project, we will examine all three methods for large-area films, in order to choose the best approach for our application, which requires that we reliably yield films with thicknesses on the order of 200-400nm and minimizes etching of the substrate such that they can be reused for a number of subsequent runs.

Results

Nanostructured solar cell

Here we demonstrate a 'nanowindow' solar cell that combines a nanostructured window layer with a planar absorber/junction (Fig 3a). In addition to carrier confinement and higher lateral conductance of conventional window layer, this nanostructured window layer serves as a broadband, angle-independent antireflection layer, thus eliminating the need for multi-layer antireflection coatings, such as the MgF_2/ZnS bilayer coating commonly used for GaAs solar cells. We demonstrate for the first time that both the optical and electrical properties in a nanostructured solar cell are enhanced simultaneously.

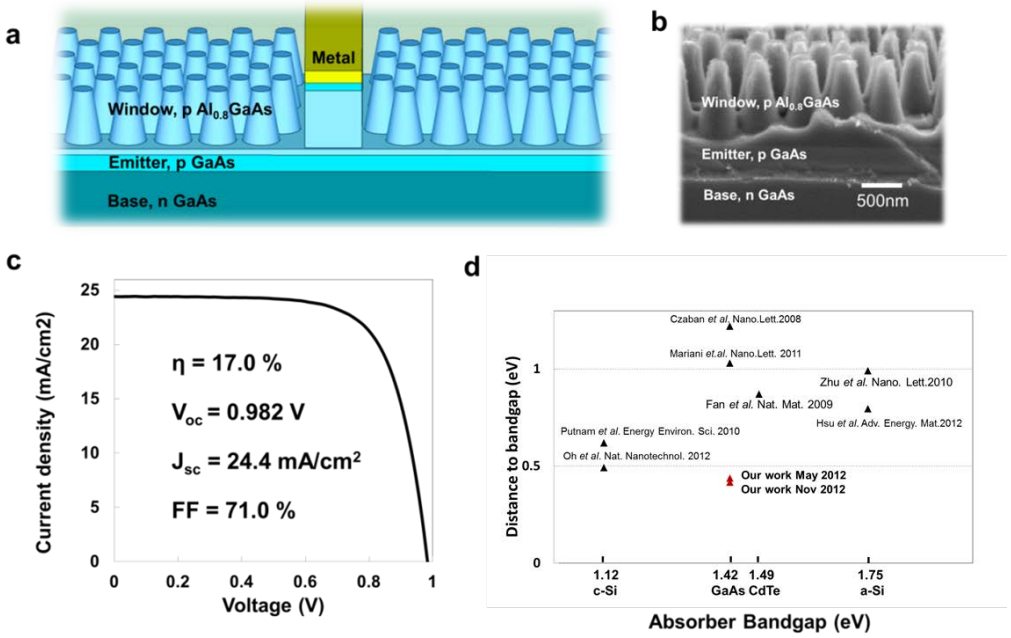

Figure 3. Overview of an AlGaAs/GaAs nanostructured window solar cell. (a) Schematic of the device structure. (b) SEM cross-section image of the solar cell active region with $Al_{0.8}GaAs$ nanocone window layer. (c) 1 Sun J-V characterizations of the best sample. (d) band gap-voltage offset (E_g/q - V_{oc}) for several published nanostructured solar cells with absorber materials of c-Si, GaAs, CdTe and a-Si.

This AlGaAs/GaAs nanostructured window solar cell has achieved the overall energy conversion efficiency, η = 17.0% and J_{sc} = 24.4 mA/cm^2, V_{oc} = 0.982 V, FF = 71% under AM 1.5G normal illumination (1000 W/m^2, 1 sun) at room temperature shown in Fig. 3c. This is compared to efficiencies of less than 5% for previously reported nanostructured GaAs solar cells[30] due to degraded V_{oc} and FF. This nano-window GaAs solar cell demonstrates both enhanced optical and electrical properties, thus not only high photocurrent was achieved, but also high V_{oc}, FF and overall efficiency. Figure 3d is a plot of the band gap-voltage offset ($E_g - qV_{oc}$) for a number of published nanostructured solar cells with absorbers of c-Si, GaAs, CdTe and a-Si against their bandgap E_g. Our nanostructured window solar cell has a V_{oc} only 0.438 V lower than the GaAs bandgap (1.42 eV). In another AlGaAs/GaAs nanostructured window cell, we achieved a V_{oc} of 1.003 V, only 0.417 V lower than the GaAs bandgap, though the overall efficiency was 16.3%, slightly lower than the cell reported in Figure 2. The small band gap-voltage offset reflects a low non-radiative recombination loss in our AlGaAs/GaAs nanostructured window solar cells. We believe that by optimizing our doping levels and growth conditions, V_{oc} and efficiency for a nanostructured window solar cell can compete with the very best planar solar cells.

GaAs epitaxial lift-off techniques

In our proposed fabrication process design for the Si/GaAs tandem cell, a key part of this process is to peel off large areas of GaAs thin film cells from the GaAs substrate. We successfully peeled off nanostructured 160nm thick GaAs thin films with XeF2 etching the Ge sacrificial layer. These peeled off nanostructured thin films show absorption enhancement over the whole spectrum from 350nm to 900nm indicating substantial light-trapping capabilities. The overall number of photons absorbed by this nano-structured thin film is equivalent to a planar structure with 1μm thickness. It is 100% enhanced compared to a similar planar control device. Thus a doubling of the short circuit current and higher carrier density in the thin absorber with increased Voc will yield higher conversion efficiency than a conventional GaAs cell.

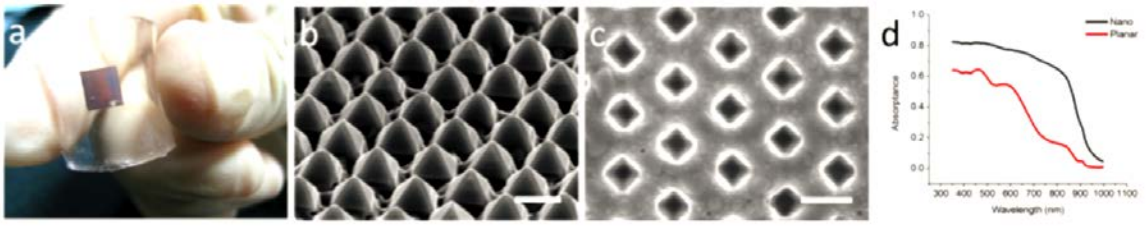

Figure 4. Characterizations of nanopyramid GaAs thin film. (a) Photograph of a bent 160nm-thick nanostructured GaAs film embedded in PDMS. SEM views of nanopyramid film (b) top surface and (c) back surface. Scale bars on (b) and (c) are 500nm. (d) Optical absorption spectra of nanopyramid film (black), planar film (red).

Large area thin single-crystal Si fabrication

We have also made progress on fabricating large-area thin single-crystal Si down to 2μm. As a concept demonstration, we developed a KOH etching method to etch thick Si wafer from 250μm down to 2μm. We have processed a series of thin-film Si with thicknesses from to 20 to 2μm. We are developing nanoscale photon management structures and processing for solar cell fabrication.

Experiments on the fundamental physics of nanophotonic light trapping

As the development of high performance solar cells is a costly exercise, it is important to develop an inexpensive and easy-to-implement platform that enables experimental verification and optimization of proposed light trapping layers. This platform can be used to study the basic physics of new, nanoscale light trapping structures in a clean and well-characterized system. It also will allow identification of the most promising structures that can be subsequently incorporated in high performance cells. For this purpose, we utilize a simple, inexpensive photo-detector platform based on silicon-on-insulator (SOI) technology. This platform was developed during a previous GCEP-funded program and a schematic is shown in Fig. 5. SOI wafers are commercially available and detectors can be fabricated inexpensively by leveraging mature Si processing techniques. The placement of scattering structures on top of such a detector enables a direct, quantitative measurement of light trapping enhancement through a simple photocurrent measurement. Photocurrent measurements are performed as a function of wavelength using an available white light source coupled to a monochromator. These measurements will enable us to assess the spectral dependence of the photocurrent enhancement produce by different types of scatterers. The large (~100 μm^2) detector area enables rapid screening of large numbers of novel scatterer designs.

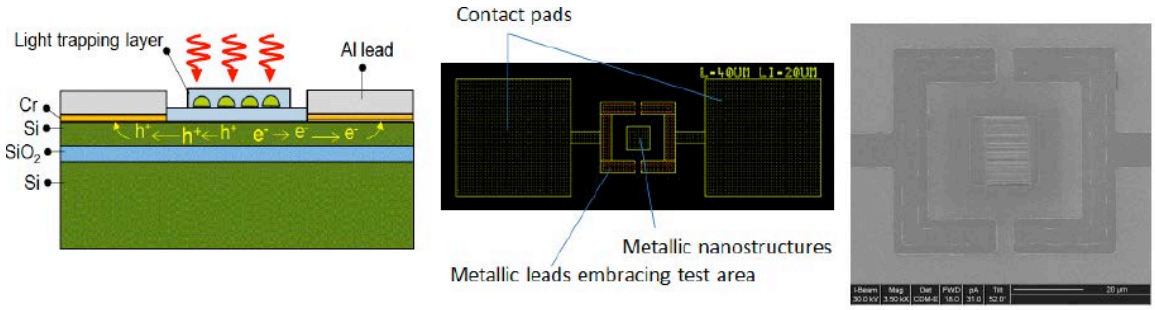

Figure 5: A schematic of our rapid light trapping prototyping platform based on silicon-on-insulator (SOI) technology. A light-trapping layer with nanostructures will concentrate light into a thin Si layer and produce electron-hole pairs. These charges will be separated and extracted via metallic (Schottky) contacts placed laterally next to the light-trapping layer. The enhancement in photocurrent over a reference region without a light-trapping layer will provide a quantitative measurement of the performance of the light trapping structures. (Middle) Photolithography mask of one test structure that shows the electrical contact pads and the area in which we can generate/place scatterers (up to now mostly simple metallic nanostructures). (Right) SEM image of the central test area showing the wrap-around electrical contacts for good carrier collection and a patterned metallic grating structure that was investigated for its light trapping ability.

Our team has recently shown theoretically that combining metals and dielectrics can lead to super-scattering nanowires with its scattering cross-section far exceeding its

geometric cross-section [31] (Fig. 5a). The key behind this approach is that such nanostructures possess a very limited number of optical modes that critically depend on the material choice, size, shape, and environment. Their near-field coupling and intermodal interference can be tailored to realize new composite particles with desired scattering properties including both the scattering cross-section and the angular distribution of the scattered light. Here, we propose to incorporate such nanowire structures on a planar silicon substrate for light trapping purposes (Fig.5b). Fig.5c shows the preliminary SEM picture of a Si nanowire structure that is partially overcoated with a metal. Our team is currently investigating these structures for use as high performance photodetectors. By combining the metals and semiconductors in nanostructures, light can be concentrated in the semiconductor to locally produce more photocurrent while simultaneously enhancing light trapping by scattering light into the guided mode of the film.

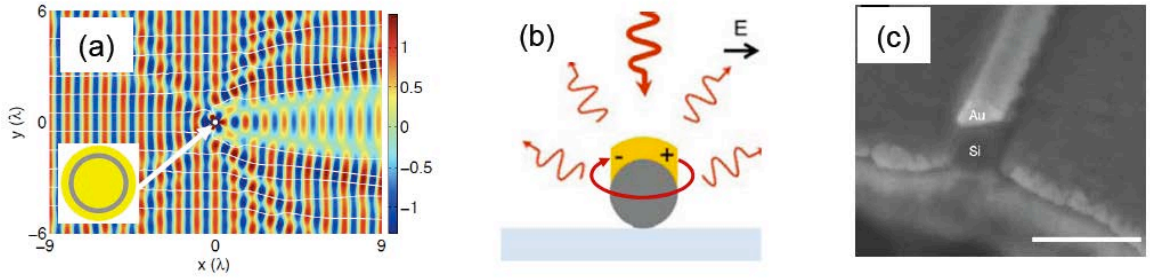

Figure 6: (a) A super-scattering nanowire consisting of metal (yellow) and dielectric (gray) regions in its cross-section as shown in the inset. (b) A light trapping scheme consisting of placing such super-scattering nanowires as shown in (a) onto a silicon substrate. (c) A scanning electron micrograph of a metal-coated silicon nanowire.

As preliminary experiment to studying the light trapping properties of metal-coated Si nanowires and particles, we first produced Si nanowire antennas by a chemical vapor deposition growth method. These antennas were drop-cast onto the detector platform. Figure 6 a shows an optical micrograph of the drop-cast wires. We focus on the wire labeled “1” here. From the AFM topography measurements we determined the wire’s diameter as 90 nm. If we scan a 800 nm wavelength illumination beam polarized transverse to the wires (TE) across the region in Fig. 6a we generate a photocurrent enhancement map shown in Fig. 6b. We observed a significant photocurrent enhancement as compared to the surrounding bare detector, demonstrating an optical antenna effect. We also note that other diameter wires, such as the 150 nm diameter wire 2, do not show strong enhancement at this wavelength and polarization.

We also measured the spectral response of the nanowire antenna. Fig. 6c shows the spectral photocurrent enhancement quantified in terms of the incoupling cross-section (ratio of coupled and absorbed in the Si layer divided by the incident light power onto the geometrical surface of the nanowire). The peaks in the spectrum are due to leaky-mode/Mie resonances of the Si nanowire that create high resonant fields within the silicon wire and in the surrounding near-field. To illustrate this we performed full field

simulations of the wire-on-detector geometry resulting in a simulated incoupling cross-section spectrum in Fig. 6d. We observe good peak-position and reasonable peak-height agreement between experimental and simulated spectra. In these spectra we note a relatively sharp peak at 500 nm and a broader feature near 800 nm wavelength. At these wavelengths we plot the magnetic field distributions of the wire/detector system in Figs 5e and 5f. At $\lambda = 500$ nm we observe two lobes within the Si nanowire illustrating the TE_{11} (i.e. transverse electric 11 mode) symmetry. Similarly at $\lambda = 800$ nm we observe a single lobe in the Si nanowire corresponding to the TE_{01} resonance of the wire. In both cases the resonant scattering causes an increased field intensity in the active Si layer below and thus produces the peaks in photocurrent enhancement.

After showing good agreement between the calculated and measured resonant behavior of both Si nanowire antennas, we are now in the process of designing metal-coated semiconductor nanowires and particles that are expected to have larger scattering/incoupling cross sections than the bare structures.

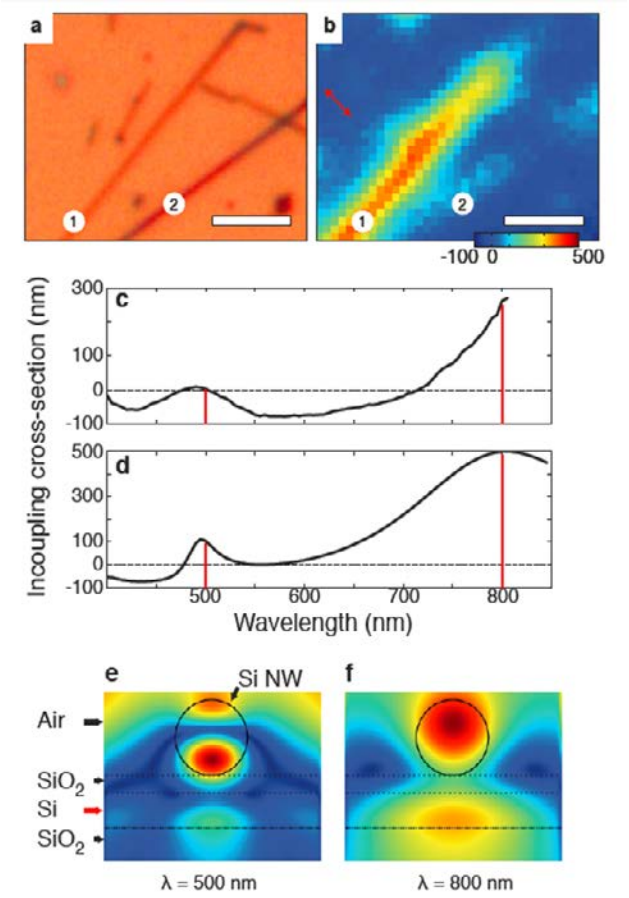

Figure 6: Spatial and spectral mapping of photocurrent enhancement from a silicon nanowire optical antenna. (a) Optical microscope image of Si nanowires on top of detector platform. Scale bar is 5 μm. (b) Photocurrent enhancement map at $\lambda = 800$ nm of the same region as (a). Units are incoupling cross-section (nm). Polarization is denoted by red arrows. Scale bar is 5 μm. (c) Experimentally measured incoupling cross-section of Si nanowire antenna of wire 1 with a polarization transverse (TE) to the wire (135◦ from horizontal). (d) Simulated TE incoupling cross-section of 90 nm Si nanowire on detector platform. (e,f) Full field simulations of the TE illuminated nanowire on the detector platform at (g) λ =500 nm and (f) λ =800 nm. Longitudinal (out-of-plane) magnetic field is shown. These illustrate how wire resonances

create high near-field intensities in the active detector layer.

Future Plans

The result from our nanowindow GaAs solar cells is promising. The novel cell architecture allows a high quality planar junction which therefore avoids the fundamental V_{oc} degradation in traditional nanostructured junction solar cells. By optimizing the cell structures, over 20% efficiency is expected. We are currently focusing on the carrier collection mechanism in nanowindow solar cells with graded bandgap to improve quantum efficiency at short wavelength. We are also exploring more suitable material with less self-absorption for the nano-window layer to further improve the nano-window cell performance.

In addition, we are investigating the epitaxial lift off and wafer bonding techniques for GaAs/Si tandem solar cells. We have utilized 2μm thick GaAs films bonded on glass with the chemical wet etching approach. By optimizing the curve on glass and other process parameters, the GaAs film with thicknesses on the order of 200-400nm can be achieved. We're also interest in applying controlled spalling technique to our Ge sacrificial layer approach. On the other side, GaAs substrate reuse after peeling off GaAs thin film solar cell layer will be studied.

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Publications:

1. D. Liang, Y. Huo, Y. Kang, K. Wang, A. Gu, M. Tan, Z. Yu, S. Li, J. Jia, X. Bao, S. Wang, Y. Yao, H.-S. P. Wong, S. Fan, Y. Cui, J. S. Harris, “Optical absorption enhancement in freestanding GaAs thin film nanopyramid arrays”, Adv. Energy Matls. 2 (10), pp 1254-1260, October 2012 (SEM of nanopyramid structure appeared on front cover of Advanced Energy Materials)
2. Dong Liang, Yangsen Kang, Yijie Huo, Yusi Chen, Yi Cui, James S. Harris, "High-Efficiency Nanostructured Window GaAs solar cells", submitted to Nature Nanotechnology, April, 2013

Presentations:

1. J. S. Harris, “Materials Challenges for Solar Cells” International Nano-Optoelectronic Workshop (iNOW), Stanford, CA, August 2012 (invited)
2. J. S. Harris, “Development of Dilute Nitride Lasers, Solar Cells and Lessons Learned”, BK21/ISRC/CISS Seminar, Seoul National University Seoul, Korea, September 2012 (invited)
3. J. S. Harris, “High Efficiency Multi-Junction Solar Cells” Shockley Alumni Reunion, Stanford, CA, October 12, 2012
4. J. S. Harris, “Development of Dilute Nitride Materials and High Efficiency Multi-junction Solar Cells”, Innovative PV Symposium, Tsukuba University, Japan, January 22, 2013 (invited)
5. J. S. Harris, “Materials Challenges for High Efficiency Multi-Junction Solar Cells”, RCAST University of Tokyo Seminar, January 23, 2013 (invited)
6. J. S. Harris, “Quest for High Efficiency Solar Cells and Lessons Learned Over a Career”, Stanford Student OSA Chapter SUPR Retreat, Sonoma, CA, April 13, 2013 (invited)