A two junction, four terminal photovoltaic device for enhanced light to electric power conversion using a low-cost dichroic mirror

Sven Rühle,[1] Akiba Segal,[2] Ayelet Vilan,[2,3] Sarah R. Kurtz,[4] Larissa Grinis,[1] Arie Zaban,[1,a)] Igor Lubomirsky,[3,a)] and David Cahen[3,a)]
[1]*Department of Chemistry, Bar-Ilan University, Ramat Gan 52900, Israel*
[2]*Department of Chemical Research Support, Weizmann Institute of Science, Rehovot 76100, Israel*
[3]*Department of Materials & Interfaces, Weizmann Institute of Science, Rehovot 76100, Israel*
[4]*National Renewable Energy Laboratory, Golden, Colorado 80401, USA*

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A low-cost dichroic mirror can be used successfully for solar spectrum splitting to enhance solar to electrical energy conversion. The mirror is optimized for use with a polycrystalline silicon photovoltaic cell (pc-Si). With the dichroic mirror *simultaneous* excitation of a medium-efficient (11.1%) commercial pc-Si and a custom-made high band gap GaInP cell (12.3%), yields 16.8% efficiency, with both cells operating at maximum power. Our results clearly show that what is missing for this simple low-cost enhancement of Si solar cell efficiency are *low-cost* high band gap cells. © *2009 American Institute of Physics.* [DOI: 10.1063/1.3081510]

I. INTRODUCTION

The photovoltaic (PV) industry is growing at annual rates of >40%.[1] Even though the price of PV-generated electricity has dropped by 5%/year over the past 15 years,[2] only significant further decrease can make it a major global electricity source. This can be achieved by lowering the production cost of PV modules and/or by an increase of their conversion efficiency. In single *p*-*n* junction cells a large fraction of solar energy is lost due to unabsorbed photons with energy below the band gap and to thermalization of the excited electrons generated by photons with energy above the band gap energy. These losses limit the theoretical terrestrial efficiency of single junction PV cells to ~31%.[3] So-called third generation PV aims to overcome this limitation either with multiple band gap devices, photon up- or downconversion, impact ionization (multiple exciton generation), or thermal methods.[4–7] Experimentally, 40.8% efficiency was achieved with a three-junction tandem device using concentrated sunlight.[8–10] Recently a 42.8% efficiency was calculated, based on individual measurements of two separate two-junction tandem systems using concentrated light with a dichroic mirror for spectral splitting.[11] The common series connection in tandem cells requires identical photocurrents from the individual junctions and is a disadvantage if illumination differs from standard conditions (AM1.5D or AM1.5G), due to atmospheric variations. The high cost of the high efficiency multijunction cells[12] limits their use to high light concentration, motivating a search for lower-cost options that can be used at low or no optical concentration.

Here we present a PV device with a conversion efficiency of 16.8% without light concentration, based on presently commercially available pc-Si technology, in conjunction with a low-cost

[a)]Authors to whom correspondence should be addressed. Electronic mail: David.Cahen@weizmann.ac.il; Igor.Lubomirsky@weizmann.ac.il; zabana@mail.biu.ac.il.

dichroic mirror (DM) and a wide band gap PV cell. In this configuration the solar spectrum is divided into a visible and infrared part, and each cell is individually operated at maximum power. The DM was designed with the following limitations imposed:

- Because of its commercial availability and widespread use we fixed that one of the cells is pc-Si, which dictated the choice of the second cell. The closest to the ideal cell that we found were the (definitely not low-cost) National Renewable Energy Laboratory (NREL) GaInP cells, developed for use in the tandem cell. We also considered a dye-sensitized solar cell (DSSC).
- To fabricate the DM only low-cost materials (TiO_2 and SiO_2) could be used, compatible with large area fabrication methods, such as sputtering or gas decomposition processes [metal organic chemical-vapor deposition (MOCVD)]. Optical coatings can be produced on large scale at low cost,[13] and the use of special optical coatings such as Ta_2O_5, HfO_2, and others were excluded, because they are expensive and impractical for the large-scale production required for solar panels.

II. EXPERIMENTAL

An optimized structure was calculated for a mirror consisting of 24 pairs of alternating layers of varying widths using FILM*STAR DESIGN software,[14] with average input parameters $n_{high}=2.28$ (TiO_2) and $n_{low}=1.46$ (SiO_2), and including the wavelength dependence of the refractive indices. Small deviations of the refractive indices over thin layers, adjacent to each interface, were taken into account, assuming that the deviation occurs over 5% of the individual layer width. The DM was produced by vacuum (e-beam) evaporation onto round glass substrates with 1 in. diameter. Optical characterization was done with a Hewlett-Packard spectrometer. A focused ion beam was used to cut a groove into the mirror to record a cross-section image with a high-resolution scanning electron microscope (SEM). Pc-Si solar cells were purchased from Silicon Solar Inc. and cut to an appropriate size (12×15 mm^2) to fit the DM. As a high band gap converter a GaInP cell (produced at NREL in a manner similar to that used for a tandem cell)[15] or a DSSC were used. The DSSC was based on a mesoporous TiO_2 film, sintered onto a conducting transparent substrate (TEC 15), sensitized with a Ru-dye (N3, purchased from Dyesol) and immersed in a I^-/I_3^- redox electrolyte, with Pt-covered FTO glass as a back electrode.[16]

Incident photon to current conversion efficiency (IPCE) measurements of the individual cells were carried out in a home-built system based on a Xe-lamp (Oriel) and a monochromator (Oriel Cornerstone 130). Reference *I-V* curves of the individual solar cells were recorded separately under simulated AM1.5G conditions (Newport solar simulator, class A). *I-V* measurements of the joint device structure were done by *simultaneously* measuring both cells using Autolab potentiostats, where the DM was tilted by 45° with respect to the incident light. The pc-Si cell was placed beneath the transmitted part of the beam, while the GaInP or DSSC cell was mounted in front of the DM to collect the reflected light [Fig. 1(a)]. Diffuse light from the sides onto the pc-Si cell was blocked by black carton, and *I-V* curves of the GaInP, and DSSC were corrected by subtracting the photocurrent that originated from diffuse light, which was measured when the DM was removed.

III. RESULTS AND DISCUSSION

IPCE spectra of the pc-Si and GaInP cell are shown in Fig. 2(a). The GaInP cell has a sharp onset of the photocurrent around 680 nm, which corresponds well to the band gap of 1.82 eV while the pc-Si cell shows an IPCE > 75% over a large spectral window (500–900 nm). The IPCE data were used to calculate the optimum cutoff wavelength of the DM, using

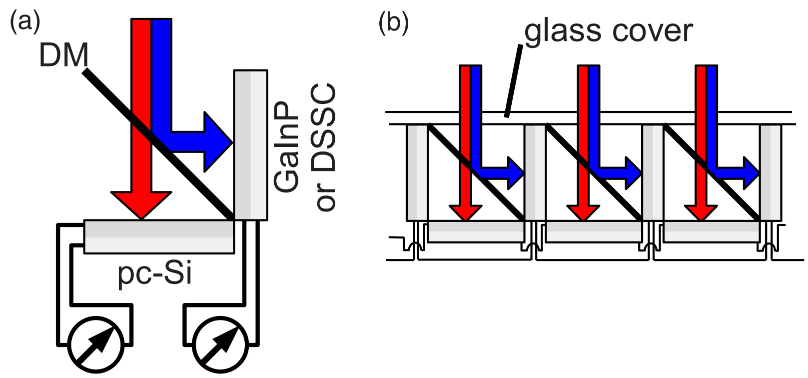

FIG. 1. (Color online) (a) Schematic of the experimental setup showing the DM with the pc-Si cell converting the transmitted light, simultaneously with the high band gap cell (GaInP or DSSC) converting the reflected light. (b) Possible design of a solar panel using spectral splitting without optical concentration.

$$P(\lambda_{\text{cutoff}}) = V_{\text{oc}}^{\text{LG}}\text{FF}^{\text{LG}}\int_{\infty}^{\lambda_{\text{cutoff}}} \Phi \cdot \text{IPCE}^{\text{LG}} \cdot \frac{q\lambda}{hc}d\lambda + V_{\text{oc}}^{\text{HG}}\text{FF}^{\text{HG}}\int_{\lambda_{\text{cutoff}}}^{0} \Phi \cdot \text{IPCE}^{\text{HG}} \cdot \frac{q\lambda}{hc}d\lambda,$$

with the open circuit voltage V_{oc} of the low band gap (LG) pc-Si cell and the high band gap (HG) GaInP cell; FF is their fill factor, Φ is the standard global irradiance at air mass 1.5 (AM1.5G), q is the elementary charge, c is the velocity of light in vacuum, h is the Planck constant, and λ is the wavelength. This calculation assumes that the DM is perfect, i.e., that transmission at wavelengths

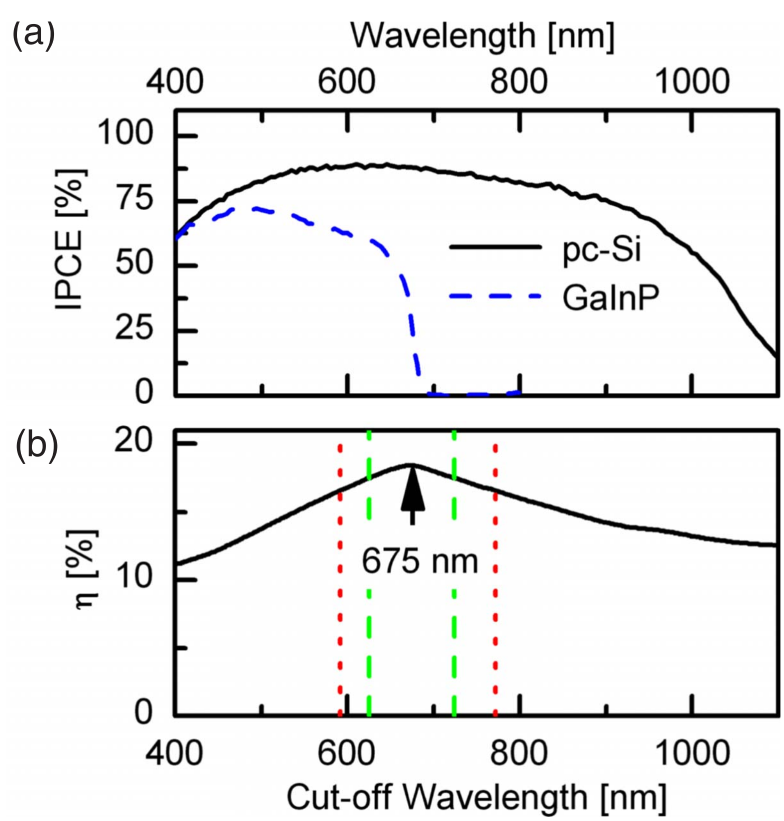

FIG. 2. (Color online) (a) IPCE of the pc-Si (black solid) and GaInP cell (blue dashed). (b) Conversion efficiency of the joint pc-Si-GaInP cells as a function of the DM cutoff wavelength.

TABLE I. Solar cell parameters of the pc-Si cell and the GaInP cell at 1 sun illumination (simulated AM1.5G) and in conjunction with the DM.

	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	η (%)
pc-Si @ 1 sun	31.8	0.55	64	11.1
GaInP @ 1 sun	11.0	1.29	87	12.3
DSSC @ 1 sun	12.5	0.73	70	6.5
pc-Si with DM (transmission)	16.4	0.53	64	5.5
GaInP with DM (reflection)	9.9	1.31	87	11.3
DSSC with DM (reflection)	11.3	0.74	69	5.7
pc-Si + GaInP	–	–	–	16.8
pc-Si + DSSC	–	–	–	11.2

below the cutoff wavelength (λ_{cutoff}) is 100% while above λ_{cutoff} reflectance is 100%. The calculated overall conversion efficiency of the two-cell system as function of λ_{cutoff} is shown in Fig. 2(b), using the pc-Si and GaInP cell parameters (V_{oc} and FF) that are summarized in Table I. A maximum conversion efficiency η of almost 18.4% is calculated for λ_{cutoff}=675 nm, which corresponds well with the IPCE onset of the GaInP cell. The dashed and dotted lines mark the wavelengths where η is 95% and 90% of η_{max}, respectively, showing that a shift of λ_{cutoff} of tens of nanometers has only a moderate effect on η. Consequently the optical requirements of the DM allow for a wide spectral cutoff region, which simplifies the manufacturing process.

Based on the calculated λ_{cutoff} the DM was designed. A schematic drawing of the stacked dielectric films is presented in Fig. 3(a) together with a cross-section SEM image in Fig. 3(b). Transmission spectra (Fig. 3(c)) show a shift of λ_{cutoff} toward higher photon energies when the incident angle increases from 0° (normal incidence) to 60°. In the near infrared the transmission decreases with increasing incident angle, but it is still around 90% at a 45° incident angle. The sharp transmission lines between 350 and 480 nm appear also in the calculated spectra (not shown) and can be attributed to the small refractive index deviations at the interfaces between the high and low index material. At 45° incident angle the transmission onset corresponds well with the IPCE of the GaInP cell.

The solar cell parameters (V_{oc}, J_{sc}, FF, and η) for the individual devices under 1 sun illumination (AM1.5) and in conjunction with the DM when measured simultaneously are summarized in Table I. The separate connection of the high band gap (GaInP or DSSC) and pc-Si cells requires additional wiring in a solar panel and doubles the number of external connections from two to four, but this configuration lifts the restriction of matched photocurrents and allows running the different cells at maximum power. With GaInP as the wide band gap cell the optical to electric power conversion efficiency increases from 11.1% for pc-Si alone to 16.8% for the joint device. Because GaInP is not exactly a cheap high band gap cell, we also used the much cheaper DSSC, which had a slightly larger photocurrent than the GaInP cell. However the overall conversion efficiency did not increase significantly compared to that of the pc-Si cell alone, because of the DSSC's poor photovoltage (relative to its optical absorption onset).

Our results, thus, drive home the need for cheap and stable high band gap, high photovoltage solar cells as the missing link for cost-effective improvement of standard pc-Si cell efficiency, something that can be very significant practically and commercially. We also note that today's Si solar cells are optimized to perform well over a relatively wide spectral range, including photon energies of up to three times the Si band gap. Relatively good performance at the high energy region of the spectrum comes, in part, at the expense of the performance at low energies (1 to 1.8 times the band gap) and at considerable manufacturing costs. The availability of low-cost high band gap cells would, in the proposed configuration, free Si solar cells from the need to perform well at the high energy part of the spectrum, which will allow design simplification and, thus, lower manufacturing costs.

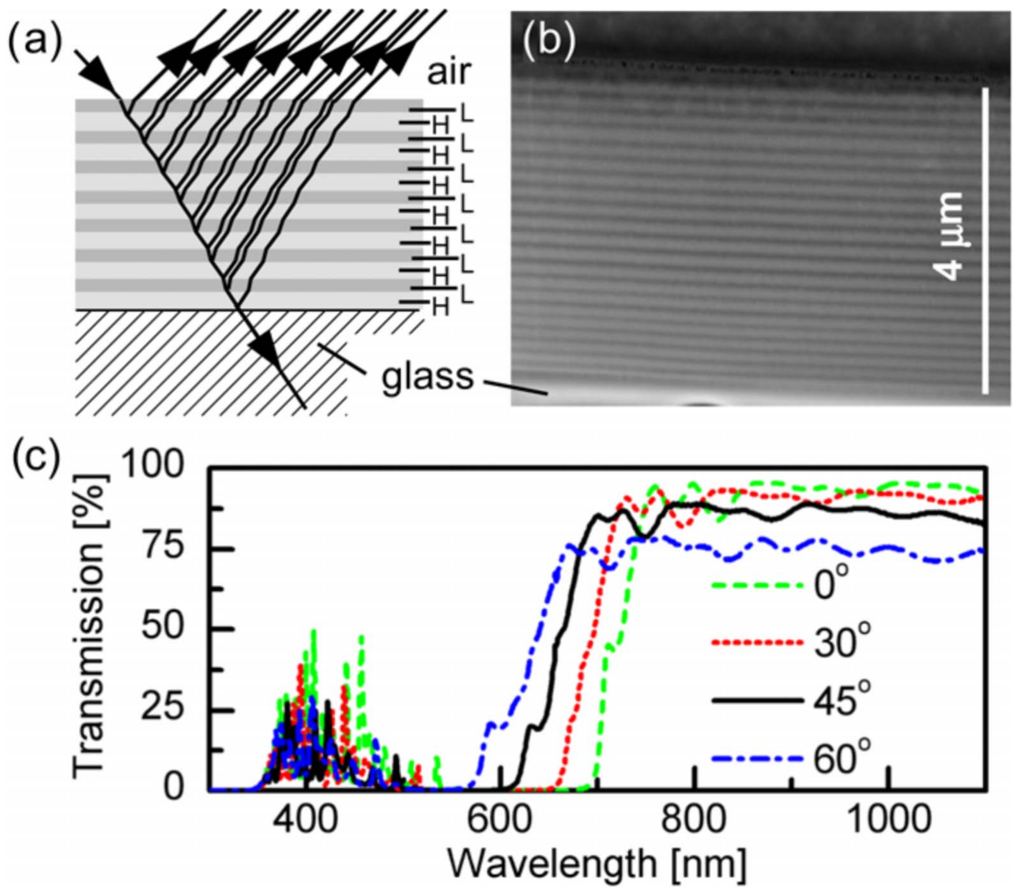

FIG. 3. (Color online) (a) Schematic of the DM with alternating high (H) and low (L) refractive index material. (b) SEM cross-section image of the DM, showing 23 L and H layers (the top two layers were removed separately for better cross-section quality). (c) Transmission spectra measured at different angles of incidence to the DM.

IV. CONCLUSIONS

In summary, we have demonstrated an almost 50% increase in conversion efficiency of a medium efficient commercial pc-Si from 11.1% to 16.8% using additionally a DM in conjunction with a wide band gap GaInP cell. While the DM can in general be produced at low cost, no cheap alternative to GaInP is currently available. This emphasizes the need for research and development in the field of high band gap PV cells, which generate a photovoltage significantly above 1 V.

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