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Broadband light trapping is numerically demonstrated in ultra-thin solar cells composed of a flat amorphous silicon absorber layer deposited on a silver mirror. A one-dimensional silver array is used to enhance light absorption in the visible spectral range with low polarization and angle dependencies. In addition, the metallic nanowires play the role of transparent electrodes. We predict a short-circuit current density of 14.6 mA/cm² for a solar cell with a 90 nm-thick amorphous silicon absorber layer. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4758468]

Thin film solar cells based on amorphous silicon are a promising solution to achieve low-cost and efficient photovoltaic devices. 1 This technology has many advantages as it uses an abundant and non-toxic material which can be deposited at low temperature and on large areas. The latest record of 10% efficiency for an hydrogenated amorphous silicon (a-Si:H) solar cell was achieved in 2009 with a 250 nm-thick active layer. 2 Reducing further the thickness of the absorbing layer could lead to higher open-circuit voltages 3 and thereby boost the solar cell conversion efficiency. In addition, for a-Si:H, the use of a thinner active layer increases the stability of the cell under light soaking. 4, 5 Achieving efficient light absorption within ultra-thin active layers (thickness ≤ 100 nm) requires advanced concepts of light management; losses in contact layers must also be reduced. Due to their ability to confine light in small volumes, plasmonic nanostructures have been proposed to enhance light absorption in photovoltaic devices. 6–10 It has been shown that sinusoidal gratings 11 and two-dimensional nanoparticles 12–14 patterned on the back contact allow the incident light to couple with guided modes supported by the a-Si:H layer. Yet, the growth of amorphous silicon on textured substrates results in a higher defect density as demonstrated by Söderström 15 and Python. 16

In this paper, we propose a design for broadband light trapping in ultra-thin amorphous silicon solar cells using a one-dimensional (1D) silver array embedded in the front layer of the cell. We demonstrate numerically that, despite the polarization selectivity of the structure, broadband absorption is achieved in the flat absorbing layer with low polarization and angle dependencies. We analyze the physical mechanism behind the absorption enhancement in the red part of the solar spectrum (λ > 600 nm). In addition, the metallic nanowires play the role of transparent conductive electrodes. This results in a short-circuit current density (Jsc) of 14.6 mA/cm² with a 90 nm-thick a-Si:H absorber layer.

The optical properties of the structures are simulated with fully vectorial numerical calculations obtained with a rigorous coupled-wave analysis method. 17, 18 For TM polarization (magnetic field parallel to the wires), the field calculation in the cell is performed with a semi-analytical treatment 19 for the sake of accuracy. The metallic parts (back contact and grating) are made of silver. Optical constants of silver (Ag) and silicon nitride (Si3N4) are taken from Ref. 20 and Ref. 21 respectively. The refractive indices of a-Si:H, indium tin oxide (ITO), and aluminum doped zinc oxide (ZnO:Al) were measured by ellipsometry.

We first consider a reference structure corresponding to a conventional a-Si:H solar cell deposited on a silver mirror: Ag/ZnO:Al (15 nm)/a-Si:H (90 nm)/ITO (70 nm). We use numerical simulations to design the thicknesses of the stack in order to maximize the integrated absorption at normal incidence, while keeping an absorber layer thinner than 100 nm. The absorption spectrum of this reference structure is shown in Fig. 1 (dashed curve). The spectral photon flux density corresponding to the normalized AM1.5 G solar spectrum Φ1.5s(λ) is shown as a reference (grey curve). The reference cell exhibits an absorption maximum in the 450–550 nm wavelength range because of a broad Fabry-Perot-like resonance in the multilayer stack. However, the absorption efficiency drops in the red part of the solar spectrum (λ > 600 nm). In addition, the use of ITO as a front contact layer results in poor a-Si:H absorption at short wavelengths. Our objective is to show that the performance of this optimized structure can be further enhanced by an alternative front contact made of metal nanowire electrodes.

The optimization of transparent conductive electrodes using metallic films as an alternative to ITO front layers has been investigated in recent theoretical 22 and experimental 23–25 works. In Ref. 23, two-dimensional networks of silver nanowires patterned on glass are shown to exhibit lower sheet resistance and larger optical transmittance than those achieved with 80 nm-thick ITO layers. Therefore, we propose to replace the ITO layer by a thin 1D metallic grating...
embedded in a transparent anti-reflection coating layer, so that the collection of current relies only on the metallic nanowires. The sheet resistance $R_s$ of a silver 1D mesh is given by $R_s = \rho p/\omega h_m$, where $\rho = 1.59 \times 10^{-8} \Omega \cdot \text{m}$ is the bulk resistivity of Ag, $p$ is the grating period, $\omega$ the width of the wires, and $h_m = 20 \text{ nm}$ is the metal thickness. In our case, in the direction parallel to the wires, we obtain estimated values of $R_s$ between 0.8 $\Omega$/sq for a non-patterned metallic film to 8 $\Omega$/sq for $w/p = 0.1$ (Ref. 22) (to be compared with $R_s \approx 60 \Omega$/sq for the reference structure with a top ITO layer\textsuperscript{23}).

The ultra-thin a-Si:H solar cell considered in the following is displayed in Fig. 1 (inset). The 1D silver grating is covered by a 60 nm-thick Si$_3$N$_4$ layer. We have added two spacing layers above (ITO, 10 nm) and below (ZnO:Al, 15 nm) the a-Si:H layer to prevent diffusion of the metal. Light transmission is avoided by the use of a silver mirror as back contact. Figure 1 displays the absorption spectra resulting from this optimization procedure, with the same a-Si:H layer thickness as the reference structure ($h_m = 90 \text{ nm}$). The parameters of the optimized grating are $h_m = 20 \text{ nm}$, $w = 80 \text{ nm}$, and $p = 200 \text{ nm}$. The absorption intensity in the a-Si:H absorber layer is calculated for both TM (magnetic polarization) and TE (electric polarization) light polarizations at normal incidence. The structure investigated has a 90 nm-thick a-Si:H absorber layer. The grating parameters are $h_m = 20 \text{ nm}$, $w = 80 \text{ nm}$, and $p = 200 \text{ nm}$. The normalized AM1.5 G solar spectrum is shown as a reference (grey curve). Dashed curve: absorption spectrum of the reference structure (same thickness, ITO front layer (70 nm), no grating).

Optimizing these resonance wavelengths. The periodicity dependence is illustrated in Fig. 2, for (a) TM and (b) TE polarizations. The spectral shift can be attributed to the excitation of guided modes in the multilayer structure via grating coupling\textsuperscript{11,13,26,27}. The electric field intensity is plotted in Fig. 2(c) for each resonance wavelength. In TM polarization, the plasmonic nature of the guided modes is identified through the field enhancement close to the metal. In TE polarization, the guided mode is mainly confined in the a-Si:H layer, leading to slightly lower metal absorption.

The absorption spectrum $A(\lambda)$ within the a-Si:H active layer is used to predict the performances of the solar cell. The theoretical short-circuit current density $J_{SC}$ is calculated for AM1.5 G solar illumination with the expression

\begin{equation}
J_{SC} = q \int \frac{A(\lambda) \Phi_{1.5}(\lambda) \lambda}{h c} d\lambda,
\end{equation}

assuming that all generated carriers are collected. In Eq. (1), $q$ is the electron charge, $h$ is the Planck constant, and $c$ is the light speed. A short-circuit current density of 14.6 mA/cm$^2$ is obtained for a 90 nm-thick a-Si:H absorber layer at normal incidence, which represents a gain of 0.6 mA/cm$^2$ with respect to the reference cell. A theoretical conversion efficiency of 9% is predicted using state-of-the-art values for the electrical characteristics of the device (open-circuit voltage $V_{OC} = 0.88$ V and fill factor FF = 0.7 (Ref. 11)). We also investigate the dependence of $J_{SC} \lambda$ with the angle of incidence $\theta$ of the impinging photons (plane of incidence perpendicular to the nanowires) for an unpolarized incident light. We find that the short-circuit current density of the optimized structure weakly depends on the angle of incidence and the polarization of the incident light (see the inset of Fig. 3). For $\theta = 70^\circ$, the $J_{SC}$ value still represents more than 80% of the short-circuit current density at normal incidence.

We expect several beneficial effects of the present architecture on the electrical properties of the cell with respect to conventional amorphous silicon solar cells. First, the use of a thin p-i-n junction should provide a better stability of the cell
against light-induced degradation. Due to the Staebler-Wronski effect, defects are created in the bandgap during light soaking thereby degrading the photoconductivity of a-Si:H. Decreasing the intrinsic layer thickness allows to maintain an effective carrier collection in spite of the additional recombination centers.5

Second, a thinner p-i-n junction exhibits a decrease of bulk recombinations and thus of the dark current $I_{\text{dark}}$. It thereby should lead to an increase of the open-circuit voltage $V_{\text{OC}}$.

$V_{\text{OC}} = n \frac{kT}{q} \ln \left( \frac{I_{\text{ph}} + 1}{I_0} \right) $, where $k$ is the Boltzmann constant, $T$ is the temperature, and $n$ is the ideality factor of the diode. $I_{\text{ph}}$ and $I_0$ are the photogenerated and saturation currents, respectively, and $I_{\text{dark}} = I_0 \left( e^{V_{\text{OC}}/kT} - 1 \right)$.

Third, as previously mentioned, it has been shown that the growth of amorphous silicon on a textured substrate leads to an increase of the open-circuit voltage $V_{\text{OC}}$.

Angular dependence of the integrated short-circuit current density. The values of $J_{\text{SC}}$ are normalized with respect to the value at normal incidence (equal to 14.6 mA/cm²).

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