Integration of a-Ge:H nanocavity solar cells in tandem devices

CrossMark

Volker Steenhoff[*], Alex Neumüller, Oleg Sergeev, Martin Vehse, Carsten Agert

NEXT ENERGY EWE Research Centre for Energy Technology at the University of Oldenburg, Carl von Ossietzky-Str. 15, 26129 Oldenburg, Germany

ARTICLE INFO

ABSTRACT

By taking advantage of spectrally broad resonances, nanocavity-enhanced a-Ge:H solar cells with an absorber layer thickness below 20 nm can reach current densities similar to micron-thick μc-Si:H devices. However, as nanocavity-enhanced devices are highly reliant on interference effects, further spectrally narrow resonance patterns are generated if an additional top cell is added to form a multi-junction solar cell. This may complicate the integration of a-Ge:H nanocavity solar cells in tandem devices. We show that conventionally textured TCO substrates can be employed to suppress the top cell induced interferences, while the required broadband resonance of the a-Ge:H bottom cell nanocavity is maintained. This approach is realized in an a-Si:H/a-Ge:H tandem solar cell with an only 20 nm thick a-Ge:H bottom cell absorber. The spectrally broad quantum efficiency curve of the bottom cell corresponds to a photocurrent density of 12.3 mA cm^{-2}, which is comparable to values reached in micromorph devices.

1. Introduction

Silicon thin-film solar cells feature several advantages over other commercially available solar cell technologies. They are based on environment-friendly and abundant materials, and can be fabricated with comparably low energy consumption. Low film thicknesses and low deposition temperatures allow their fabrication on flexible and lightweight substrates [1], suggesting high potential for cost reduction on the module level as well as for use in special applications such as lightweight construction roofs.

To increase the efficiency of the silicon thin-film solar cell technology, tandem devices have been developed over the last 20 years which consist of an amorphous silicon (a-Si:H) top cell and a microcrystalline silicon (μc-Si:H) bottom cell [1,2]. This way, the lower thermalization losses of the a-Si:H top cell for short-wavelength light can be combined with the ability of μc-Si:H to absorb light having longer wavelengths. However, to match the current-densities of both sub cells, more than 1 μm thick μc-Si:H bottom cells are typically required, while the top cell has a thickness of only about 300 nm. Hence, while the gain in cell efficiency is moderate compared to an a-Si:H single cell (12.7% vs. 10.2% [3]), prolonged deposition time leads to significantly increased fabrication costs.

To address this issue, microcrystalline silicon–germanium alloys (μc-SiGe:H) have been investigated as alternative low bandgap absorbers [4,5]. Alloying germanium to silicon increases the

absorption coefficient and lowers the bandgap of the material. Unfortunately, the electronic properties strongly degrade with increasing germanium content, implying a rather limited potential for use in electro-optical devices. Although amorphous silicon–germanium alloys (a-SiGe:H) have also been studied as replacement of the μc-Si:H solar cells [6,7], a germanium content close to 100% is required to take advantage of the same spectral range as in μc-Si:H solar cells. In fact, pristine amorphous germanium (a-Ge:H) of highest electronic quality exhibits an optical bandgap of about 1.1 eV, which is very similar to the mobility bandgap of μc-Si:H. On the other hand, this material suffers from an approximately ten times higher defect density compared to a-Si:H [8,9]. For this reason, solar cells using 100 nm thick high-quality a-Ge:H absorber layers have reached efficiencies of only about 3.5%, up to now [10]. Hence, it is helpful to reduce the absorber thickness to a few tens of nanometers to enable an efficient charge carrier collection. However, for such thin layers, efficient light absorption can only be achieved by applying a highly efficient light-trapping concept.

As we have recently demonstrated, light-trapping can be addressed by using a Fabry-Pérot resonator to enhance the absorption of photons with energies slightly above the absorber bandgap [11]. Such nanocavities have drawn attention due to their ability to produce strong and spectrally broad interference patterns [12–14]. Depending on the phase jumps that light undergoes when it is reflected at the resonator surfaces, the required optical cavity length can be much lower than 1/4 of the wavelength for which resonant enhancement is desired. This leads to spectrally broad resonances rather than narrow interference patterns. Together with the exceptionally high absorption coefficient of

* Corresponding author.
E-mail address: Volker.Steenhoff@next-energy.de (V. Steenhoff).

a-Ge:H, this enables a current density of 20 mA cm^{-2} in an a-Ge:H solar cell with an only 13 nm thick absorber layer [11]. Although the cell efficiency has not been increased significantly compared to the best results reported by Zhu et al. [10], a value of 3.6% has been reached with absorber material of lower quality. Apart from the particular case of a-Ge:H solar cells, this concept is also interesting for devices based on other highly absorbing materials which exhibit low charge carrier mobility-lifetime products.

In view of the goal to replace the μc-Si:H absorber in a-Si:H/μc-Si:H solar cells, the question arises of how such nanocavity-enhanced solar cells can be integrated into multijunction concepts. We use 1-dimensional optical simulations of an a-Si:H/a-Ge:H tandem device to show that additional top cell induced resonances strongly modify the infrared absorption of the bottom device compared to the single cell result. An approach to solve this problem is discussed and implemented in first a-Si:H/a-Ge:H tandem solar cells.

2. Methods

2.1. Simulation

One-dimensional optical simulations have been performed in order to calculate quantum efficiency (QE) spectra of single and tandem solar cells. Calculations were carried out using the software package Scout/Code (W. Theiss Hard- and Software). Complex refractive index data were taken from literature (a-Ge:H [8] and silver [15]) or were obtained by ellipsometric spectroscopy and subsequent modeling of the measured spectra (a-Si:H, μc-Si:H), respectively. For ZnO, data were taken from the database provided with Scout/Code. Quantum efficiency (QE) spectra were calculated by simulating absorption spectra of the absorber layers (i.e. only for the a-Ge:H layer of the a-Ge:H cell) and assuming full charge carrier extraction. Short circuit current densities were afterwards calculated from these spectra by convolution with the AM1.5g spectrum.

2.2. Experimental

Glass/ZnO:Al substrates (size: 10×10 cm^2) with an RMS surface roughness of 50 nm and 120 nm, respectively, have been used for our tandem cell experiments (high surface roughness has been achieved using wet-chemical etching [16]). Silicon and germanium layers were deposited onto these substrates using the grounded electrode of a parallel-plate plasma-enhanced chemical vapor deposition (PECVD) reactor which was operated at a frequency of 13.56 Mhz. H$_2$-diluted GeH$_4$ and SiH$_4$ were used as precursor gases for germanium and silicon deposition, respectively. B$_2$H$_6$ and PH$_3$ were added to achieve p- and n-doping of the silicon layers, respectively. All silicon layers were produced at a temperature of 200 °C. For top cell depositions, a H$_2$/SiH$_4$ ratio of 20, a pressure of 3 Torr and an rf power density of 30 mW cm^{-2} was used in all layers. The amorphous silicon layers of the bottom cell were fabricated at a H$_2$/SiH$_4$ ratio of 5, pressure of 0.75 Torr and an rf power density of 30 mW cm^{-2}. For μc-Si:H deposition, we used a H$_2$/SiH$_4$ ratio of 500, 150 mW cm^{-2} rf power density and a pressure of 2.25 Torr. For a general overview on the properties and fabrication of a-Si:H and μc-Si:H layers, we refer the reader to [17]. Germanium layers were fabricated at a substrate temperature of approximately 160 °C at a pressure of 0.6 Torr, 16 mm electrode distance and an RF power density of 500 mW cm^{-2}. A H$_2$/GeH$_4$ ratio of 40 was used. While deposition rates near 1 nm s^{-1} are achieved in our standard process, we have reduced the rate to approximately 0.1 nm s^{-1} by pulsing the plasma with a duty cycle of 10% at 3 kHz. This was done to decrease the impact of the plasma ignition phase on the absorber thickness. The PECVD deposition of all a-Ge:H bottom cells was carried out in a multi-chamber cluster tool (type CS400PS, Von Ardenne Anlagentechnik GmbH). The top cells were fabricated using a PECVD in-line tool from Leybold Optics.

After deposition of the a-Si:H top cells, ZnO:Al intermediate reflectors were fabricated in a DC magnetron sputtering system (Von Ardenne Anlagentechnik GmbH, Al concentration 2 wt%) at a chamber temperature of 200 °C without preheating. This was followed by a 30 min annealing step under ambient conditions at 160 °C and subsequent fabrication of the bottom cell stack using PECVD. Finally, silver back contacts ($\approx$ 150 nm) were deposited by electron beam evaporation through a 1×1 cm^2 mask, followed by a second annealing step at 130 °C for 15 h. The front contacts were uncovered by using laser ablation.

Quantum efficiency (QE) spectra were determined from differential spectral response measurements. For the tandem devices, blue or infrared bias light as well as a voltage bias was applied to measure the bottom cell and top cell, respectively. As the focus of our work is to align the optical effects in nanocavity-enhanced solar cells with the concept of multijunction devices, the applied voltage bias was chosen separately for each sub-cell (and also for the single junction device) to maximize the charge carrier extraction. Hence, all QE curves yield information on the charge carrier generation efficiency rather than the external quantum efficiency under short circuit conditions.

3. Results and discussion

3.1. a-Ge:H nanocavity single cells

While a detailed explanation of the general concept of a-Ge:H nanocavity solar cells has been given before [11,12], Fig. 1 briefly illustrates the effect: Fig. 1a displays a simplified version of the a-Ge:H solar cell stack used throughout this work. The a-Ge:H
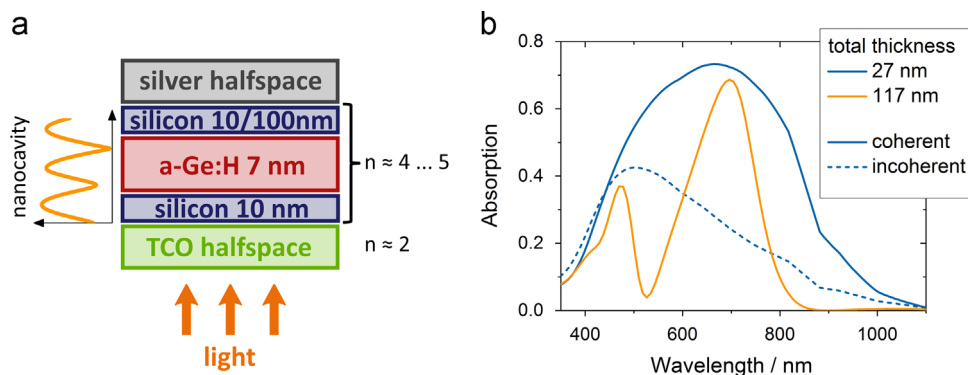

Fig. 1. (a) Simplified sketch of a nanocavity a-Ge:H solar cell. The given thickness values represent the cell stacks used for the absorption simulation presented in (b). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)