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Zinc oxide as an active n-layer and antireflection coating for silicon based heterojunction solar cell

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ABSTRACT

We report a single heterojunction solar cell model based on crystalline p-silicon and n-zinc oxide. The ZnO can act as front n-layer as well as antireflection coating saving processing cost and complexity. Experiments are performed to find optimized growth window using MOCVD to achieve maximum transmission in ZnO as front layer of the solar cell. Gallium-rich ZnO:Ga films are also grown to improve optical properties of the front layer. Optical characterizations of pristine ZnO and gallium-rich ZnO:Ga are presented. The modified PC1D software is used to find the optimized parameters for the solar cell. Absorption spectrum of ~0.5 μm thick ZnO film grown in our lab was used in the simulations to get realistic results. Simulations anticipated conversion efficiency of 19% and fill factor of 81%.

1. Introduction

Continuous increase in world population and industry will result in 100% increase in global energy consumption and CO_2 emission will rise by 150% of the current level by 2050 [1]. It is foreseeable that solar power generation can contribute prominently to overcome the indisputable problems of global warming and climate change.

The first practical solar cell was demonstrated by Bell Laboratories in 1954 using a diffused silicon (Si) p–n junction having efficiency of ~6% [2]. The Si based solar panels have become and are still most cost effective and practically feasible. Crystalline Si solar cells are approaching theoretical efficiency limit of 29.43% for a 110 μm thick solar cell [3] but the best achieved conversion efficiency using commercial solar cells is not more than 22%. Although price per watt of Si-based solar modules has dramatically reduced recently, nevertheless, low efficiency and high cost of solar cells are two main bottlenecks in widespread use of solar panels. In order to overcome these limitations, other types of solar cells should be explored.

There are several reports presenting characterization studies and improvements in Si, GaAs, and other heterostructure solar cells [4–6] using PC1D. In 2007, our group demonstrated GaN and InGaN solar cells designed by modified PC1D software [7]. The materials were grown by metal organic chemical vapor deposition (MOCVD), fabricated into devices of variable sizes and contact configurations, and characterized for material quality and performance. We have also reported various studies on PC1D based Si solar cell design and fabrication [8–11].

In this paper, we propose a new model of potentially cost effective and high efficiency single heterojunction solar cells based on Si (rear region) and the emerging II–VI material ZnO (front region). The ZnO grown on Si can work as an active n-layer as well as antireflection coating. The simulations are performed using modified PC1D software. Electrical and optical characteristics as well as internal and external quantum efficiencies are investigated by varying different key parameters. Also, we have grown ZnO thin films of the same thickness as optimized by PC1D simulations. The films were grown on sapphire substrates by custom-made MOCVD system in our lab. Optical characterization of the grown ZnO thin films is carried out experimentally. The measured absorption spectrum of the grown ZnO thin films is used in PC1D simulations in order to get more realistic results of the model.

2. Proposed model using zinc oxide

Zinc oxide is a direct wide bandgap material with bandgap tunable from 3 to 5 eV with doping or alloying. The main advantages of ZnO which make it unique as compared to other II–VI and III–V wide bandgap materials are its low processing cost, low toxicity,

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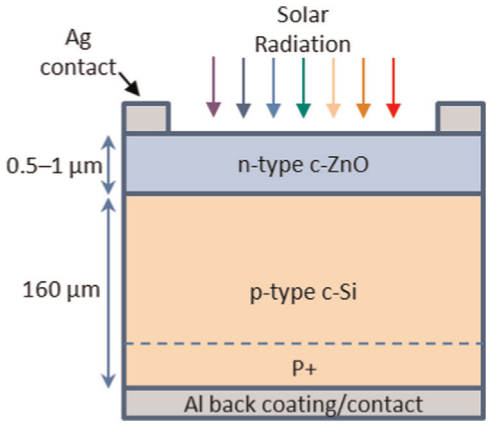

Fig. 1. Schematic showing single hetero-junction solar cell based on crystalline p+p-Si and n-ZnO. The front ZnO layer acts as n-type layer of the p–n junction as well as antireflection coating due to its close refractive index match. Furthermore, the work function of Ag is less than electron affinity of ZnO, therefore, Ag–ZnO contact at front surface are ohmic.

natural abundance, and highly stable wurtzite structure with lattice c/a ratio (1.603) very close to ideal ratio (1.633) [12]. The larger exciton binding energy of ZnO (60 meV) guarantees efficient luminescent and photovoltaic characteristics [13]. In addition, ZnO is more resistant to radiation damage as compared to Si, GaAs, and GaN which prevents photo-degradation and ensures longer device lifetime. For applications of transparent conducting oxides (TCOs), aluminum- or gallium-doped ZnO has recently gained attention as a viable substitute for indium tin oxide (ITO).

In our proposed model, front region of the solar cell which is directly exposed to solar radiation is composed of n-type ZnO. Therefore, transparency of the ZnO layer for visible and IR region is very important. In 2009, Nayak et al. [14] demonstrated Ga-doped ZnO transparent conducting thin films for optoelectronic device applications using sol–gel spin coating technique. The transparency of the films was more than 80% in the spectral range of 400–700 nm with resistivity as low as 3.3×10^{-3} Ω cm with 2 at% Ga.

Fig. 1 is the schematic of the solar cell model proposed in this study. Thicknesses of the rear and front regions are optimized by PC1D simulations. Fortunately, refractive index of ZnO is very close to the ideal value required for antireflection (AR) coating of Si surface. Therefore, ZnO layer can also substitute the AR coating for Si if the film thickness is carefully optimized for the peak wavelength of solar spectrum. The peak intensity of the solar spectrum is approximately at wavelength of 600 nm. The reflectivity at this wavelength calculated by PC1D program was 33%. The refractive index of ZnO at the same wavelength is ~2 which was calculated using Fresnel equation for normal incidence. The extinction coefficient of ZnO was measured at 600 nm and found to be negligible; therefore, it was ignored in the calculations. The refractive index of air was assumed to be 1. The refractive index of silicon at wavelength of 600 nm came out to be 3.95.

The reflection is minimized if the refractive index of the AR coating (ZnO layer in our case) is the geometrical mean of the two surrounding indices. Assuming air at one side and Si at other side, optimum refractive index of the AR coating (n_{AR}) is 1.99 at wavelength having peak intensity in solar spectrum. The refractive index of ZnO at 600 nm is ~2 which is very close to the ideal value. This can eliminate requirement of additional antireflection coating resulting in reduced fabrication process steps and cost. If glass refractive index is used instead of air considering encapsulation of solar panel then the ideal refractive index value becomes ~2.3 which is still close to refractive index of ZnO and will work for antireflection at some wavelengths of broad solar spectrum. Required thickness of ZnO layer to act as perfect AR coating can be calculated as

$$d = \frac{\lambda}{4n_{AR}} \quad (1)$$

The optimum thickness of the ZnO layer is 75 nm for $\lambda = 600$ nm. But PC1D simulations revealed that conversion efficiency does not change significantly up to 0.1 μm thickness of ZnO layer (response is rather broadband).

The optimized modeled thickness was obtained as ~0.1 μm for minimum reflection, which can be detrimental to electrical performance of the device. Because the sheet resistance of the ZnO film can be very high and will require very close gridline spacing resulting in increased shadowing. Increased shadowing decreases the short circuit current and hence the efficiency. To improve the sheet resistance, thicker ZnO films can be used that will still significantly reduce reflection (especially if textured Si is used) as compared to bare silicon. The simulations revealed that increasing ZnO film thickness from 0.1 to 0.5 μm reduces the efficiency from 19.4% to 19%. This drop in efficiency is not significant as compared to losses due to high sheet resistance and shadowing effects because of close gridline spacing.

3. Characterization using PC1D simulations

There are several adjustable parameters in PC1D which can be iterated to find an optimized window for solar cell fabrication. Since we are using ZnO only for the front region, the parameters associated with the rear region are almost same as already optimized for Al-BSF Si solar cell. We have used absorption spectrum for ZnO which was measured in our lab for film thickness of ~0.5 μm. Fig. 2 illustrates the external quantum efficiency (EQE) of the solar cell device for different thicknesses of ZnO layer. The absorption of high energy photons in ZnO is mainly responsible for poor EQE at short wavelengths.

The impact of ZnO thickness on open circuit voltage (V_{OC}), short circuit current (I_{SC}), fill factor, and power conversion efficiency of the ZnO/Si solar cell are depicted in Fig. 3. The I_{SC} reduces monotonically with increased ZnO thickness because of significant decrease in number of available photons in space charge region as shown in Fig. 2. Since most of the space charge region lays in Si due to large difference of doping in two materials, the photons reaching Si contribute most in carrier generation. Since I_{SC} is directly related with photo-generated carriers, absorption in thicker ZnO layer causes drop in I_{SC}. A slight decrease in V_{OC} with increase in ZnO thickness can be attributed to the same reason. For the optimized efficiency of the solar cell, we achieved a V_{OC} of 622 mV which is slightly lower

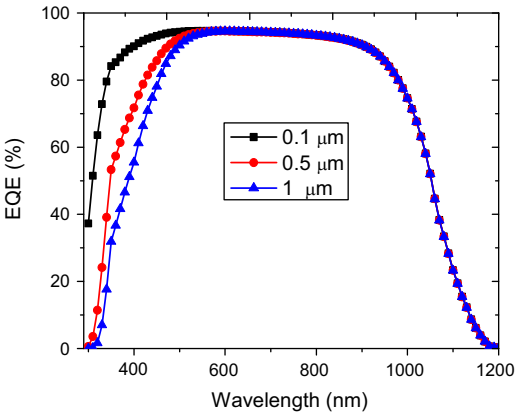

Fig. 2. External quantum efficiency (EQE) of the solar cell device for three different thicknesses of ZnO layer assuming 5% reflection from front surface.