Characteristics of field effect a-Si:H solar cells

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Abstract

Two dimensional device simulation has revealed advantages of a solar cell which utilizes an inversion layer induced by the field effect instead of a heavily doped window layer. The cell performance improvements have been predicted not only in the short circuit current due to the increased quantum efficiency for light with short wavelengths but also in the open circuit voltage and the fill factor by the use of metals with larger workfunctions. The conversion efficiency has been estimated to increase to 50% by the use of the field effect solar cell. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: aSi:H; Field effect; Solar cell

1. Introduction

It is known that the photogenerated carriers in a window layer recombine quickly and do not contribute to photocurrent [1]. To solve this problem on the window layer, the use of p-type hydrogenated amorphous silicon–carbide (a-SiC:H) was proposed [2]. The a-SiC:H window layer improved conversion efficiency but quantum efficiency for light with short wavelengths stayed much less than unity. It was also pointed out [3,4] that a Schottky junction formed between a transparent conducting oxide (TCO) and a p-type a-Si:H window layer have a negative electric field in the p-type layer to cause serious detrimental effects on the conversion efficiency. Recently, we proposed a new type of a-Si:H solar cell in which a p-type layer was designed to be induced by the field effect instead of the impurity (boron) doping. Although this design has something to do with the crystalline Si inversion layer solar cell [5], our idea further extended not only to a-Si:H cell but also to the use of a ferroelectric layer for inducing the inversion layer. We demonstrated 35% improvement in the short circuit current (Isc) due to the increased quantum efficiency for blue light by the use of this structure using a device simulator [6]. In our field effect solar cell, we can choose any metal as a top contact electrode since the top contact electrode covers only a small portion of the cell. In this paper, we report some characteristics of the field effect a-Si:H solar cell calculated with a two-dimensional device simulator focusing on the improvement of the cell performance by the choice of the contact metal.

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2. Methods of simulation

A schematic cross-section of the field effect solar cell we proposed is shown in Fig. 1. In the field effect cell structure, the p-type window layer, which could cause degradation in photo-currents, does not exist except for the region just under the front contact metal. The purpose of the p-type layer under the front comb electrode is to assure the large and stable built-in voltage. In practice, this structure can be achieved by etching of p-type layer using the front contact metal as a mask. The width and spacing of the comb front contact were assumed to be 1 μm and 30 μm, respectively, which can be easily defined using a conventional photo-lithography technique. The electric field across the insulator to form the surface inversion layer can be achieved by several methods, which include the use of fixed charge in the insulator [7] and the use of ferroelectric materials. In this simulation, we assumed, for simplicity, that the structure has a transparent electrode with a negative applied voltage on a thin insulator to induce field effect. It is well known that the inversion layers at the insulator/a-Si:H interface can be easily achieved by negative voltages and has been commonly used for a-Si:H thin film transistors (TFTs).

Most parameters used in this simulation except for the mobility gap were taken from Chatterjee’s [3] and Koinuma et al.’s [6] paper. Surface recombination velocity at the indium tin oxide (ITO) a-Si:H interface was assumed to be $10^{7}$ cm/s, which is close to thermal velocities of carriers. Although reflectivity at the backside metal was assumed to be 0.8, reflection at the front surface was not taken into account to concentrate on intrinsic performance of the cells. For simulation of defective materials such as amorphous Si, it is important to model deep levels in its forbidden gap appropriately. We assumed distribution of donor-like levels in the lower half of the forbidden gap and acceptor-like deep levels in the upper half. This distribution is almost identical to that assumed in reference [3]. The donor-like states become positive when they ionize, while the acceptor-like states become negative. For p-type and n-type layers, higher deep level concentration ($6 \times 10^{18}$ cm$^{-3}$) than that for the intrinsic layer was assumed because heavy doping causes formation of extra defects. No additional trap was assumed at the insulator/a-Si:H interface because the field effect cell is not sensitive to the interface trap due to the high electric field near the interface [5]. Photo-currents of conventional p-i-n cells can be improved theoretically by reducing the thickness of p-type window layer [3]. We assumed 200 Å thick p-type layer because the p-type layer thinner than 200 Å is difficult to deposit uniformly and often causes serious decrease in Voc [8]. The thickness of intrinsic layer for both samples was assumed to be 500 nm. It was already confirmed that the inversion layer resistance does not affect properties under these conditions [6].

Since the field effect cell involves carrier motion in both lateral and vertical directions to the surface, it is essential to analyze this cell using a two dimensional simulator. We used TMA’s MEDICI two-dimensional device simulator. The simulations were based on the simultaneous solution of the hole- and electron-continuity equations and Poisson’s equation. Although most research groups assumed that the temperature is 0 K to determine the ionized trap concentration, we used the Shockley–Read–Hall expression to obtain the trap occupation function. The recombination rate for this material can be calculated using the Shockley–Read–Hall expression.

3. Results

As we reported earlier [6], the short circuit current (Isc) of the field effect cell is 35% larger than that of the conventional cell due to the improvement in the quantum efficiency for blue light, although both cells have the similar open circuit voltages (Voc). There is a possibility of further improvements in the performance of the field effect cell if we use a metal for the comb electrode which is different from TCO.
Fig. 2. $I-V$ characteristics of the field effect cell with various work functions for the top comb electrodes. Lines are drawn as guides for the eyes.

Fig. 2 shows $I-V$ characteristics of the field effect solar cells with various workfunctions for the top comb electrodes. As can be seen in Fig. 2, $I-V$ characteristics strongly depend upon the work function of the comb electrode. The open circuit voltages and the fill factors estimated from this figure are shown in Fig. 3. With the increase in the electrode work function, we can obtain the improved Voc and fill factor, which saturate at a work function of about 5.5 eV. Fig. 4 shows how the maximum output power depends upon the work function. Improvement in the conversion efficiency by the use of the field effect solar cell structure over a conventional cell has been estimated to be as high as 50% in spite of the area loss by the non-transparent comb electrodes. Therefore, a-Si:H solar cells with this structure are promising for future low cost solar power plants.

4. Discussion

The mechanisms for these improvements are best understood by investigating the band diagrams near the junction between the comb electrode and p-type a-Si:H. Fig. 5 shows the energy band diagram under the comb electrodes with work functions of 5.15 eV and 5.5 eV. In the band diagram with 5.15 eV work function, a negative electric field is clearly seen in the entire p-type region. This energy band diagram is basically the same as for conventional cells [6]. On the other hand, in the case of the cell with the 5.5 eV work function, the band is pulled up at the metal/a-Si:H interface. Hence, the built-in potential is effectively increased when it is forward-biased, which should lead to the large open circuit voltages and the
large fill factors. In practice, the comb electrodes with large work function can be easily fabricated by an evaporation of noble metals such as gold. One clear drawback of this approach is reduction in the effective area due to the use of non-transparent metal. However, this problem becomes less important if we use a fine photo-lithography technique.

5. Conclusions

The field effect a-Si:H solar cell structure increases the short circuit current due to the improved quantum efficiency for blue light but also increases the open circuit voltage (Voc) and the fill factor of the field effect a-Si:H solar cell by the use of comb electrodes with larger work functions. Since the total improvement in the conversion efficiency by the use of the field effect cell structure is large (50%) and the fabrication process is compatible with that for the conventional p-i-n cell, this structure is promising as a future generation low cost photovoltaic cell.

Acknowledgements

The authors wish to thank Technology Modeling Associates, for its help in device simulation. This work was supported by NEDO International Joint Research Grant.

References