Device simulation and fabrication of field effect solar cells

KAORI MIYAZAKI*, NOBUYUKI MATSUKI, HIROYUKI SHINNO, HIROSHI FUJIOKA[†],
MASAHARU OSHIMA[†] and HIDEOMI KOINUMA

Ceramic Materials and Structures Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama-shi, Kanagawa, 226-8503, Japan

[†]Department of Applied Chemistry, The University of Tokyo, 7-3-1 Hongou Bunkyo-ku, Tokyo, 113-8656, Japan

Abstract. The performance of a novel hydrogenated amorphous silicon (*a*-Si:H) solar cell which utilizes the field effect solar cell (FESC) has been investigated both theoretically and experimentally. The theoretical analysis has been done for both *p*- and *n*-channel FESCs by employing a two-dimensional device simulator which is based on current continuity and Poisson equations. The calculated performance is compared with that of conventional (*p-i-n*) *a*-Si:H solar cells. The calculation demonstrated that both *n*-channel and *p*-channel FESCs could improve the conversion efficiency by as much as 50%.

In order to check the reliability of simulation, the transport properties of intrinsic *a*-Si:H film and thin film transistor (TFT) have also been calculated and compared with the experimentally obtained characteristics. Experimental verification of TFT and FESC has been attempted by using MgO and *a*-SiN:H as dielectric layer materials. Preliminary results are presented.

Keywords. Two-dimensional device simulation; field effect; *a*-Si:H; solar cell.

1. Introduction

Despite its high possibility of large scale and low cost production, hydrogenated amorphous silicon (*a*-Si:H) solar cells still suffer from low conversion efficiency and photo instability. A main reason for the low efficiency is the high localized state density in the high-dope window layer.

Recently, we proposed a new type of *a*-Si:H solar cell in which *p*-type layer is designed to be induced by the field effect (FE) instead of the impurity doping (Koinuma *et al* 1996). This new structure is expected to eliminate the window layer problem mentioned above. In addition, we can use any metal, instead of a transparent conductive oxide, as top contact (comb) electrode, since it covers only a small portion of the cell. Thus, we have a freedom of choosing a metal with proper work function. A two-dimensional device simulation supported our concept; the collection efficiency for short wavelength light was calculated to increase remarkably in the FESC. Improvements in the open circuit voltage (V_{oc}) and the fill factor (FF) were also predicted by the use of comb electrodes with large work functions (Fujioka *et al* 1998). In these calculations, we employed *p*-channel FESCs in view of the fact that *p-i-n* structures have been exclusively used in conventional cells. In this paper, we deploy our device simulation to *n*-channel FESC and thin film transistor as well.

2. Device simulation

Since the FESC involves carrier motion in both lateral and vertical directions to the surface, it is essential to analyze the cell characteristics using a two-dimensional simulator. We employed SILVACO's ATLAS for two-dimensional device simulation using the current continuity and the Poisson equations. Different from the frequently used assumption that the temperature is 0 K to determine the ionized trap concentration, we used accurate Shockley–Read–Hall (Hall 1952) expression at 300 K to obtain both the trap occupation function and recombination rate.

The solar cell performances of dielectric/*a*-Si:H *i-n*/metal (*p*-channel FE) and dielectric/*a*-Si:H *i-p*/metal (*n*-channel FE) cells (figure 1) are calculated and compared with those of conventional *p-i-n*, i.e. ITO/*a*-Si:H *p-i-n*/metal and *n-i-p*, i.e. ITO/*a*-Si:H *n-i-p*/metal cells. The width of the comb front contact is assumed to be 1 μm . The electric field across the insulator to form the surface inversion layer can be achieved either by the use of fixed charge in the insulator (Hezel and Schörner 1981) or the application of bias to a dielectric or ferroelectric material. In our simulation, we chose the bias application to MOS (metal–dielectric oxide–*a*-Si:H semiconductor) structure for simplicity.

For simulation of such a defective material as *a*-Si:H, it is important to model a deep level in the energy gap appropriately. We assumed the exponential tail and Gaussian localized distribution (Shaw and Hack 1988). The donor-like states become positive when they ionize, while the acceptor-like states become negative. No

*Author for correspondence

additional trap is assumed at the insulator/*a*-Si:H interface because our cell is not sensitive to the interface trap due to the high electric field near the interface (Kuwano *et al* 1981).

For performing the device simulation with this structure, there are many material and structural parameters as

shown in figure 1, which include density of defect states (N_D and N_G), capture cross section, mobility (μ_e and μ_h), refractive index (n and k), dielectric constant (ϵ_r), work function (Φ), surface velocity, mobility gap (E_g), doping concentration, FE-induced charge density, film thickness (d), and spacing of the comb front contacts (l). In this

Figure 1. Schematic cross-sections of *p*-channel (a) and *n*-channel (b) FESCs, a sample to calculate conductivity of *i*-*a*-Si:H (c), and an *a*-Si:H TFT (d).

Table 1. Parameters for simulation.

Mobility gap	1.7 eV
Mobility (electron)	$25 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$
Mobility (hole)	$6 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$
Charge capture cross-section	$1 \times 10^{-14} \text{ cm}^2$
Neutral capture cross-section	$1 \times 10^{-16} \text{ cm}^2$
Donor tail energy	46 meV
Acceptor tail energy	27 meV
Gap state density in <i>i</i> -layer	$1.5 \times 10^{15} \text{ cm}^{-3} \cdot \text{eV}^{-1}$
Gap state density in doping layer	$6.0 \times 10^{18} \text{ cm}^{-3} \cdot \text{eV}^{-1}$
Effective density of states at conduction/valence band edge	$2 \times 10^{20} \text{ cm}^{-3} / 2 \times 10^{20} \text{ cm}^{-3}$
Thickness of <i>p</i> -type/ <i>n</i> -type layer	200 Å/200 Å
Doping concentration in <i>p</i> -type layer	$6 \times 10^{18} \text{ cm}^{-3}$
Doping concentration in <i>n</i> -type layer	$6 \times 10^{18} \text{ cm}^{-3}$
Photon flux	AM-1.5 100 $\text{mW} \cdot \text{cm}^{-2}$
Reflectance at the front side of <i>a</i> -Si:H layer	0.2
Reflectance at the back side of <i>a</i> -Si:H layer	0.8
Absorptance of TCO layer for conventional cells	0.1
Absorptance of dielectric layer for FESCs	0.0
Absorption coefficient of <i>a</i> -Si:H	Literature values (Piller 1985)
Induced charge density at the interface	5×10^{12} and $1 \times 10^{13} \text{ cm}^{-2}$
<i>i</i> -layer thickness	0.3 ~ 0.7 μm
Comb electrode spacing	15 μm ~ 200 μm

study, we focus on the effects of intrinsic (*i*) layer thickness and the distance between comb-electrodes. The *i*-layer thickness ranges from 3000 Å to 7000 Å. The comb-electrode distance is varied from 15 µm to 200 µm. The FE-induced charge is fixed at 5×10^{12} or $1 \times 10^{13} \text{ cm}^{-2}$. The light intensity is AM-1.5, 100 mW/cm². The parameters used in the calculation are listed in table 1.

3. Experimental

To check the validity of the simulation, a thin film transistor (TFT) using MgO dielectric layer was fabricated and their electric property was compared with the calculation. Structure of the TFT is shown in figure 1d. First, a 1.2 µm thick MgO dielectric layer was deposited on an ITO/glass substrate by pulsed laser deposition (PLD) at a substrate temperature of 350°C. Then, a 1900 Å thick intrinsic *a*-Si:H was deposited by plasma CVD. Finally, aluminum source and drain electrodes were deposited (L/W = 60 µm/2.7 mm) on the *a*-Si:H by the vacuum evaporation.

Figure 2. I - V characteristic of *i*-*a*-Si:H under the light irradiation and dark condition.

4. Results

4.1 Characteristics of intrinsic *a*-Si:H

In order to validate the parameters for *a*-Si:H, the conductivities of intrinsic *a*-Si:H (*i*-*a*-Si:H) have been calculated by the same simulator. The schematic cross-section of the structure used to calculate conductivities is shown in figure 1c. Photo and dark currents of *i*-*a*-Si:H are calculated under AM-1.5 100 mW/cm² and $1 \times 10^{-15} \text{ mW/cm}^2$ light irradiation, respectively. Figure 2 shows the I - V characteristics of *i*-*a*-Si:H under light and dark conditions. Photo and dark conductivities are evaluated to be $2 \times 10^{-4} \text{ S/cm}$ and $9 \times 10^{-9} \text{ S/cm}$, respectively, which are consistent with observed values.

4.2 Thin film transistor

V_G - I_D characteristics calculated by taking the dielectric/semiconductor interface defects into account agreed well with the best reported data (Tsukada 1991). Figure 3 shows the V_D - I_D characteristics we obtained in our *a*-Si:H/MgO/ITO structure. However, it was not so good probably due to the leakage and/or insufficient resistivity in MgO layer. The calculated on/off ratio varies from 10^5 to 10^{10} with the decrease in the interface defect density from $5 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$ to zero, while that of our TFT is 10^3 .

4.3 Field effect solar cell

The typical *i*-layer thickness and the spacings of the comb front contacts both for *n*- and *p*-channel cells

Figure 3. Experimental I_D - V_D characteristics of an *a*-Si:H TFT.

(figures 1a, b) are $0.5\ \mu\text{m}$ and $30\ \mu\text{m}$, respectively. In the dark, the energy band diagrams along the interface between the dielectric and $a\text{-Si:H}$ are flat. However, light irradiation causes a band bending. The band profile along the interface of the n -channel FESC becomes concave while that of the p -channel FESC becomes convex. The concaved band allows electrons at the interface to move to the comb-electrodes and the convex band diagram allows holes to move to the comb-electrodes. Therefore, electrons of the n -channel FESC whose majority carrier at the interface is electron, can reach the comb-electrodes, and holes of the p -channel FESC whose majority carrier at the interface is hole, can reach the comb-electrodes.

The possible maximum output powers of various types of $a\text{-Si:H}$ solar cells are calculated as a function of i -layer thickness. The n - and p -channel FESCs with a comb front contact spacing of $30\ \mu\text{m}$ give powers higher than the conventional $p\text{-i-n}$ cell. The i -layer thickness to give the maximum output power for the n -channel FESC and $n\text{-i-p}$ junction are about $0.4\ \mu\text{m}$, which are thinner than those ($0.6\ \mu\text{m}$) for the p -channel FESC and $p\text{-i-n}$ junction cell.

Figure 4 shows the possible maximum output powers of $a\text{-Si:H}$ solar cells calculated as a function of the comb electrode spacing. The n -channel FESC shows smaller spacing dependence of the maximum output power. This result should be noted as an advantage of n -channel cell in view of the generally accepted notion that $p\text{-i-n}$ cell is better than $n\text{-i-p}$ cell.

5. Discussion

The maximum output powers for both n - and p -channel FESCs are larger than those for conventional cells. This can be presumed to come from the fact that the FESCs use window layers induced by the field effect instead of the impurity doped layers and that the FESCs can take any metals as a top contact electrode instead of TCO at the cost of effective area. The doping free window layer brings the improvement in short-circuit current (I_{sc}) due to the increased quantum efficiency for light with short wavelength. The work function of the comb electrode changes the barrier height, which directly influence V_{oc} and FF . For the n -channel FESCs, the smaller work functions of comb-electrodes lead to smaller Schottky barriers. Hence, we can improve the V_{oc} and FF by the use of a comb electrode with a small work function.

The maximum output powers for n -channel FESCs with comb electrode spacings $< 50\ \mu\text{m}$ are slightly smaller than those for p -channel FESCs. This can be attributed to the difference in the type of the carriers which drift in the direction normal to the surface. It is well known that the mobility of hole in $a\text{-Si:H}$ is much smaller

than that of electron. Since a large portion of carriers in the $a\text{-Si:H}$ are generated near the surface, holes in the n -channel FESCs must travel long distance, which in turn results in the higher possibility of recombination with the electrons. This difference in the type of carriers gives the result that the optimum i -layer thicknesses give the maximum output power for the n -channel FESC and $n\text{-i-p}$ junction are slightly smaller than those for the p -channel FESC and $p\text{-i-n}$ junction. The short hole drift distance is essentially important for the n -channel FESCs, while the large volume in which the hole-electron pairs are generated is important for the p -channel FESCs.

On the other hand, n -channel FESCs with long comb electrode spacing show higher efficiency when they are compared with p -channel FESCs with the same spacings. For the FESCs with large comb electrode spacing, the lateral motion of the carriers limits the cell performance. In the n -channel cells, we can take advantage of high mobility of the electrons in this lateral transportation. The use of n -channel cells allows us to use low cost printing technique for the production of FESCs, which makes the n -channel cells attractive for mass-production.

6. Conclusion

Our simulation has shown that both n - and p -channel $a\text{-Si:H}$ FESCs offer better performance than conventional cells. Furthermore, n -channel FESCs with comb electrode

Figure 4. Maximum output power profiles calculated as a function of the comb front electrode spacing. The i -layer thickness and FE-induced charge density were assumed to be $0.4\ \mu\text{m}$ for n -channel FESC and $n\text{-i-p}$ junction, $0.6\ \mu\text{m}$ for p -channel FESC and $p\text{-i-n}$ junction, and $1 \times 10^{13}\ \text{cm}^{-2}$.

spacing as wide as 100 μm can give conversion efficiencies maintained at levels higher than conventional *p-i-n* cell. The electric characteristics of the *a*-Si : H TFT calculated by taking the dielectric/semiconductor interface defects agree well with the best reported data, but our preliminary result was not so good. Further studies are in progress to verify the possibility of FESC.

Acknowledgements

Authors wish to thank SILVACO Inc. for its support in device simulation. This work was supported by NEDO International Joint Research Grant.

References

- Fujioka H, Oshima M, Hu C, Matsuki N, Miyazaki K and Koinuma H 1998 *J. Non-Cryst. Solids* **227-230** 1287
- Hall R N 1952 *Phys. Rev.* **87** 387
- Hezel R and Schörner R 1981 *J. Appl. Phys.* **52** 3076
- Koinuma H, Fujioka H, Hu C, Koida T and Kawasaki M 1996 *Mater. Res. Soc. Symp. Proc.* **426** 95
- Kuwano Y, Fukatsu T, Imai T, Ohnishi M, Nishiwaki H and Tsuda S 1981 *Jpn J. Appl. Phys. supp.* **20** 20
- Piller H 1985 *Handbook of optical constants of solids* (Academic Press Inc.)
- Shaw T and Hack M 1988 *J. Appl. Phys.* **64** 19 457
- Tsukada T 1991 *Digest 49th annual device research conf.* (Colorado: IEEE Electron Devices Society) **IA-3**