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Characteristics of Silicon Inversion Layer Solar Cells

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Fundamental characteristics of silicon inversion layer (IL) solar cells using SiO/Si as an active region and $Mg/SiO_2/Si$ as an MIS junction are studied. Methods to estimate the degree of inversion at the Si surface of the cells are established. The degree of inversion gives significant effects on energy conversion efficiency. The optimum preparation condition of the SiO film which makes inversion at the Si surface is investigated to make inversion stronger. In order to decrease the sheet resistance and to optimize the thickness of the insulator for MIS junctions, effects of thermal oxidation of the Si surface is studied. Photovoltaic properties of the Si IL solar cells with different resistivities are measured. The AM 1 efficiency of 13.5% was obtained.

§1. Introduction

Silicon inversion layer (IL) solar cells shown in Fig. 1 have been studied as a new type of solar cells.[1-4] The SiO film contains positive charges which attract electrons (minority carriers) to the *p*-Si surface. When the SiO film contains sufficient positive charges, the conduction type at the *p*-Si surface is inverted to *n*-type and an induced *p-n* junction is formed. The region of this induced junction (A in Fig. 1) is called an active region where electron-hole pairs are generated under illumination. The region B is the electrode which a metal-insulator-semiconductor (MIS) junction constitutes. It collects the photocurrent out of the IL solar cell. The IL solar cell has advantages such as fabrication of very shallow junction and elimination of heavy-doping effects.[5] Also, the SiO film with the suitable thickness works as a good antireflection (AR) coating. Moreover, MIS junctions can be fabricated by simple and low temperature processes.

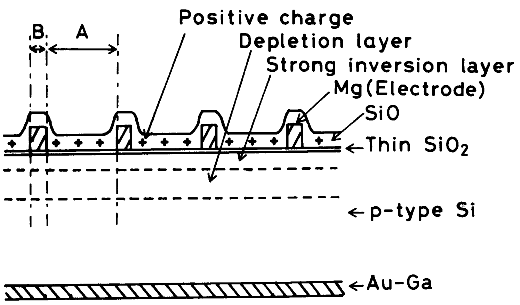

Fig. 1. Schematic diagram of Si IL solar cell.

Although AM1 efficiencies up to 18.3% for active area have been reported,[6] fundamental properties of the Si IL solar cells have not been studied yet. This paper discusses fundamental properties of the Si IL solar cells using a system of SiO/*p*-Si for the active region combined with $Mg/SiO_2/p$-Si for the MIS junction shown in Fig. 1. The MIS system of $Mg/SiO_2/p$-Si is found to behave like a *p-n* junction.[7]

§2. Sample Preparation

Mirror-polished wafers of *p*-Si (100) with the resistivities of 1–2 ohm-cm were used. Gold-gallium alloy was evaporated as an ohmic contact. A very thin oxide film (SiO_2 of about 15 Å thick) was prepared by thermal oxidation in a dry oxygen flow at around 400°C. Magnesium (Mg) was evaporated and the metal grating pattern was made by photolithography and lift-off technique. Finally, the SiO film (about 1000 Å thick) was deposited in a vacuum of about 1.33×10^{-4} Pa (1×10^{-6} Torr). The grating lines were 33 μm wide and the spacings were 142 μm wide. The total and the active areas were 0.40 and 0.33 cm^2, respectively.

§3. Experimental Results and Discussion

Figure 2 shows current-voltage (*I-V*) characteristics of the Si IL solar cells under sunlight illumination (92.7 mW/cm^2). The cell (A) gave the efficiency (η) of 10.6% (active area), the open circuit voltage (V_{oc}) of 551 mV, the short circuit current density (J_{sc}) of 27.6 mA/cm^2 (active area), and the fill factor (*FF*) of 0.648,

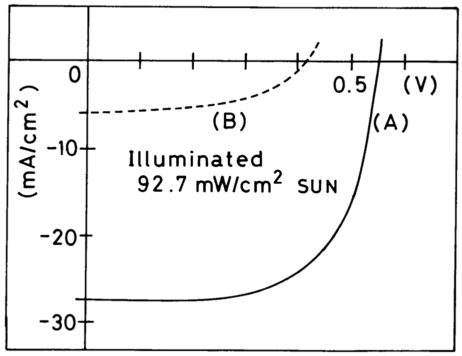

Fig. 2. Photovoltaic properties: The deposition rates of the SiO films for the cells (A) and (B) are 2.27 and 0.727 Å/sec, respectively.

while the cell (B) showed smaller values of 1.37%, 418 mV, 6.10 mA/cm^2, and 0.498. The difference between the two cells was only the deposition rate of the SiO film in the fabrication process. The deposition rates for the cells (A) and (B) were 2.27 and 0.727 Å/sec, respectively. Thus the properties of SiO films affect the photovoltaic properties remarkably.

Table I shows the relation between the SiO deposition rate and the cell efficiency together with the Auger signal ratio of oxygen (O) to Si. The optimum deposition rates to obtain high efficiencies are between 2 and 3 Å/sec. The Auger signal ratio in the optimum condition is smaller than that in other conditions, which implies that an amount of oxygen is smaller in the optimized SiO film. Since oxygen atom tends to become a negative ion, the optimized SiO film is considered to contain more positive charges which will result in strong inversion at the p-Si surface.

In order to confirm the existence of a strong inversion layer in the active region, we measured I_{sc} and FF (Fig. 3), scanning a He–Ne beam spot (100 μm diameter) as shown in Fig.

Table I. Amount of charges in SiO films with deposition rate and Auger signal ratio of O/Si.

Deposition rate (Å/sec)	Efficiency (%)	Auger signal ratio O/Si	$(C_D+C_D')/C_D$
0.727	1.30	1.85	*
1.93	11.0	/	2.52
2.99	10.4	1.49	2.83
5.14	8.68	/	1.24
9.17	4.30	1.56	1.74

*weak inversion

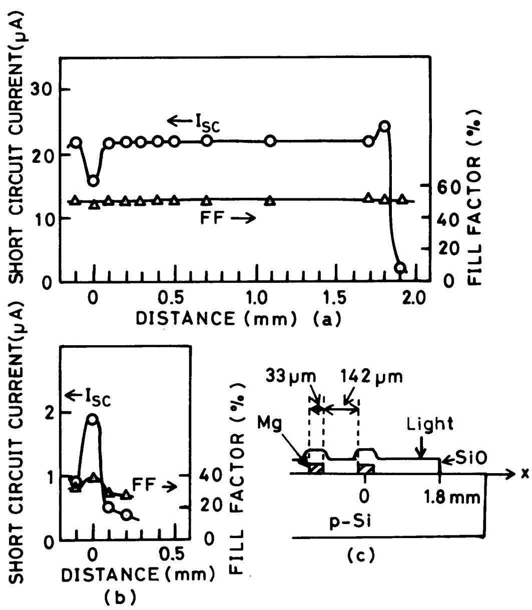

Fig. 3. Dependence of I_{sc} and FF on light spot distance, (a) of the cell (A) and (b) of the cell (B). (c) The positions of light spot and electrode.

3(c). From Figs. 3(a) and (b), for the cell (A) the large value of I_{sc} is obtained even at the light spot distance of 1.8 mm which is the end of the SiO film (Fig. 3(c)), while for the cell (B) I_{sc} drops at the distance less than 0.1 mm and the value of I_{sc} is smaller than that for the cell (A). The value of FF for the cell (A) is larger than that for the cell (B). These facts imply the existence of the strong inversion layer in the cell (A) and not in the cell (B). Therefore, the existence of the strong inversion layer is essential to obtain high efficiency.

To analyze the Si IL solar cell characteristics in detail, metal(Al)-oxide(SiO)-semiconductor (p-Si) MOS diodes were fabricated. The SiO deposition conditions were the same as those for the Si IL solar cells above mentioned. Figure 5 shows capacitance-voltage (C-V) characteristics of the MOS diodes in the dark under a high frequency condition. The diode (A) was prepared with the same SiO deposition rate as the cell (A) which has strong inversion at the p-Si surface in Fig. 2. The diode (B) was fabricated with the same SiO deposition rate as the cell (B) which has no strong inversion at the p-Si surface. The capacitance of the diode (A) increases for the positive applied voltages. When the applied voltage reaches the value which makes strong inversion at the p-Si

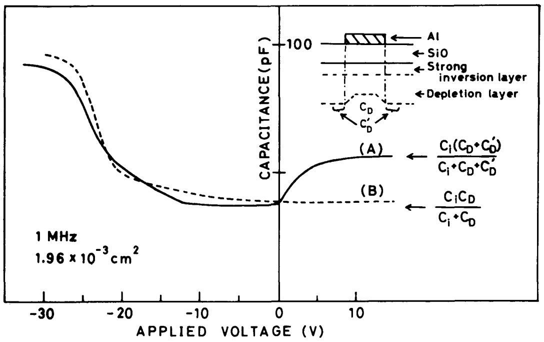

Fig. 4. *C-V* characteristics and schematic diagram of MOS diode.

surface, the inversion layer under the electrode is electrically connected with the inversion layer around the electrode induced by the positive charges in the SiO film. Therefore, the capacitance from the region around the electrode (C_D') is connected in parallel with the capacitance under the electrode (C_D) (Fig. 5). The value of $(C_D+C_D')/C_D$ becomes larger as the inversion around the electrode becomes stronger. The value for the diode (A) is 2.16. The values for other diodes are summarized in Table I. The efficiency seems to become higher in the cell with a larger value of $(C_D+C_D')/C_D$. Therefore, in order to obtain higher efficiencies, it is necessary that the SiO film contains more positive charges and that the inversion in the active region becomes stronger.

Current-voltage characteristics of the cells (A) and (B) were measured in the dark. They overlap almost entirely with each other, and the ideality factor (n) defined as $(q/kT)(\partial V/\partial \ln I)$ is about 2. Dark current is possibly transported by diffusion and recombination. The dominant current mechanism in the cells (A) and (B) should be the recombination current in the whole area of the cell, because depletion layers exist both in the MIS junction region and in the active region. Although for the cell (A) the diffusion current flows across the induced *p-n* junction in the active region, it is estimated to be smaller than the total current by the order of 10^3. In order to decrease the dark current for the increase of V_{oc}, it is necessary to use the substrates with a smaller amount of recombination centers and to avoid the increase of recombination centers in the fabrication processes such as thermal oxidation of the Si surface.

Table II. Dependence of photovoltaic properties on oxidation time.

($P_{in}=28.0$ mW/cm^2)

t (min)	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	η (%)
15	462	6.53	0.66	9.66
30	492	6.42	0.66	10.1
45	512	6.08	0.70	10.6
60	489	6.17	0.67	9.82

The oxidation condition of the Si surface gives some effects on the cell performance. The relation between the oxidation time and the cell performance is shown in Table II. The optimum oxidation time is 45 min.

In order to increase V_{oc}, lower resistivity (0.2–0.3 ohm-cm) substrates were used. The efficiency of 13.5% (active area), V_{oc} of 580 mV, J_{sc} of 36.3 mA/cm^2 (active area), and FF of 0.640 were obtained. The value of V_{oc} is expected to increase by about 100 mV compared with the case of higher resistivity (1–2 ohm-cm) substrates simply taking account of the change in Fermi level. The increase of V_{oc}, 29 mV, was small. The increase of J_{sc} is attributed to the increase of the minority-carrier diffusion length. The minority-carrier diffusion length for the lower-resistivity substrate was estimated to be longer than 200 μm by EBIC measurement and for the higher-resistivity substrate it was 140 μm. The increase of V_{oc} results from the increase of J_{sc} in the present study.

Since the sheet resistance along the inversion layer ($R_\square$) under illumination affects the efficiency in the Si IL solar cell, we estimated it from the *C-V* characteristics of MOS structures. When the sheet resistance becomes smaller, the width of the spacing can be made wider, which gives the easy photolithography process in fabrication. The sheet resistance in the dark was estimated from the following equations:[8]

$$Y_{real}=\frac{(2\pi f)^2 C_i^2 G_0}{G_0^2+\{2\pi f(C_0-C_i)\}^2},$$

$$\frac{Y_{real}}{C_D(\mathrm{inv})f}=\frac{4\pi}{\nu}\left[\frac{\mathrm{Ker}'(\nu)\mathrm{Ker}(\nu)+\mathrm{Kei}'(\nu)\mathrm{Kei}(\nu)}{\mathrm{Ker}^2(\nu)+\mathrm{Kei}^2(\nu)}\right],$$

$$\nu=\{2R_\square C_D(\mathrm{inv})f\}^{1/2},$$

where C_i is the capacitance of the insulator, C_0 and G_0 the capacitance and the conductance of the MOS diode at a sufficient high positive applied voltage, C_D(inv) the capacitance of the

Table III. Dependence of sheet resistance on preparation condition.

Type	MOS structure	$R_\square$ in the dark (kΩ/□)	$R_\square$ under illumination (kΩ/□)
Type A	Al/SiO/Si	13	4.4
		7.6	4.1
Type B	Al/SiO/very thin SiO_2/Si	8.1	1.6
		15	1.8

semiconductor at a positive applied voltage, and f the measurement frequency. The functions of Ker and Kei are the real and the imaginary parts of the modified Bessel function of the second kind, respectively, defined by $K_0(j^{1/2}v)=\mathrm{Ker}(v)+\mathrm{Kei}(v)$. It is found that these equations can be used also under illumination.[9] Table III shows the values of $R_\square$ in the dark and under illumination, where the MOS structures of type A and type B are Al/SiO/Si and Al/SiO/very thin SiO_2/Si, respectively. The values of $R_\square$ under illumination were smaller than those in the dark. The decrease of $R_\square$ under illumination compared with $R_\square$ in the dark is advantageous for solar cell performance of the Si IL solar cells. The values of $R_\square$ under illumination of type B were smaller than those of type A, although $R_\square$ of both structures in the dark were nearly equal. Therefore, thermal oxidation of the Si surface is very useful to decrease the sheet resistance under illumination. The best value of $R_\square$ under illumination was about 1.6 kΩ/□.

§4. Conclusion

Efficiencies of the Si IL solar cells are found to depend mainly on the preparation condition for the active region. Strong inversion in the active region is necessary in order to obtain high efficiencies, and higher efficiencies are obtained as the inversion in the active region becomes stronger. Thermal oxidation of the Si surface is efficient to decrease the sheet resistance under illumination in the active region and to optimize the performance of the MIS junction which affects collection efficiency of photo-generated carriers.

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References

1) R. B. Godfrey and M. A. Green: Appl. Phys. Lett. **33** (1978), 637.
2) P. V. Halen, R. P. Mertens, R. V. J. Overstraeten, R. E. Thomas and J. V. Meerbergen: IEEE Trans. Electron Devices, **ED-25** (1978), 507.
3) R. E. Thomas, R. B. North and C. E. Norman: IEEE Electron Device Lett. **EDL-1** (1980), 79.
4) R. Hezel and R. Schörner: J. Appl. Phys. **52** (1981), 3076.
5) F. A. Lindholm, A. Neugroshel, C. T. Sah, M. P. Godlewski and H. W. Brandhorst: Proc. 12th IEEE Photovoltaic Specialists Conf., 1976, p. 1.
6) M. A. Green, R. B. Godfrey, M. R. Willison and A. W. Blakers: Proc. 14th IEEE Photovoltaic Specialists Conf. 1980, p. 684.
7) H. Matsuura, S. Nishino and H. Matsunami: Jpn. J. Appl. Phys. **20**, Supplement 20–2 (1981), 51.
8) E. H. Nicollian and A. Goetzberger: IEEE Trans. Electron Devices **ED-12** (1965), 108.
9) H. Matsuura and H. Matsunami: unpublished.