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On the surface recombination current of metal-insulator semiconductor inversion layer solar cells

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Current voltage characteristics have been obtained under dark and illuminated conditions for Al-SiO$_2$-pSi metal-insulator semiconductor inversion layer solar cells. The cells were fabricated on $<100>$ and $<111>$ oriented substrates with resistivities in the range of 8–15 Ω cm. For $<111>$ cells the open circuit voltages V_{oc} were found to be lower than for $<100>$ cells. The measured differences in V_{oc} were higher than expected from the dark characteristics which is explained as a difference in the surface recombination current due to a higher interface state density N_{ss} of $<111>$ cells.

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Recently a great amount of interest has been demonstrated in metal-insulator semiconductor (MIS) solar cells because of their simple design and potentially high conversion efficiency. The role of the interfacial layer in metal-insulator-semiconductor solar cells has been treated in several papers.[1-3] The main effect of the layer is to decrease the saturation current J_0, and thereby increase the open circuit voltage V_{oc} of the solar cell.[4] When introducting a thin interfacial layer in a MIS solar cell, a large density of interface states N_{ss} is introduced. These states can have a great influence on the solar cell performance as they are acting as charge-storage centers and recombination-generations centers and provide additional tunneling paths between the metal and the semiconductor.[5,6]

In this work the Al-SiO$_2$-pSi MIS inversion layer cell[7] with a structure as shown in Fig. 1 has been examined. For this type of cell the area between the contact holes should be treated as an ideal abrupt $n^+ - p$ diode, where the n^+ inversion layer is induced at the silicon surface by the fixed positive charges located at the interface of the thermally oxidized silicon.[8] So for this part of the cell, the carrier lifetime should be high as no crystal damage has been produced by diffusion of impurities leading to a small minority carrier saturation current $J_{0,\min}$ from this region.

For the MIS structure which is formed at the contact hole region the thickness of the oxide layer is about 20Å and the results and discussion of Refs. 1–6 must be taken into consideration.

The solar cells were fabricated on 10–15 Ω cm $<111>$ and 8–10 Ω cm $<100>$ pSi wafers and current voltage characteristice were obtained under dark and illuminated conditions, using AM 1 illumination. The device fabrication technique has been reported in a recent publication.[9]

Figures 2(a) and 2(b) show the dark and illuminated characteristics obtained for some typical inversion layer cells of $<100>$ and $<111>$ orientation, respectively. For all the $<111>$ cells that have been measured there was a cross over point between the dark and the illuminated curves as seen in Fig. 2(b), but no cross over points were observed between the dark and the illuminated curves for the $<100>$ cells, Fig. 2(a).

For the inversion layer region the dark diode current can be expressed as

$$J_{\text{dark}} = J_0[\exp(qV/kT) - 1] + J_{\text{rec}}, \tag{1}$$

where J_0 is the saturation current for an abrupt $n^+ - p$ diode and J_{rec} is the sum of the surface and the depletion region recombination currents. The surface recombination current is given by

$$J_{s,\text{rec}} = qS(p_s - p_{n0}). \tag{2}$$

where p_s and p_{no} are the surface concentration and the equilibrium concentration of holes at the inversion layer, and S is the surface recombination velocity at the Si-SiO$_2$ interface given by[10]

$$S \approx \sigma_p v_{\text{th}} N_{ss}. \tag{3}$$

Here N_{ss} is the interface state density, σ_p is the capture cross section of the interface states, and v_{th} is the thermal velocity of the carriers. As the impurity concentration at the inversion layer is very small, the depletion region recombination current will only be of small significance in this case. From semiconductor theory the dark surface recombination current of Eq. (2) is given by

$$J_{s,\text{rec}} = qSp_{n0}[\exp(qV/kT) - 1], \tag{4}$$

but as S is orders of magnitude lower for a thermally oxidized silicon surface than for a diffused surface[11] the contribution from $J_{s,\text{rec}}$ to J_{dark} will be rather small when compared to a diffused junction diode. So in the dark case, the

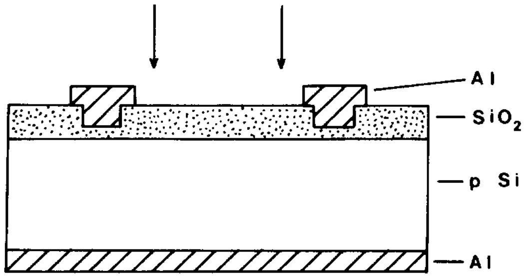

FIG. 1. Cross section of lthe Al-SiO$_2$-pSi MIS inversion layer cell.

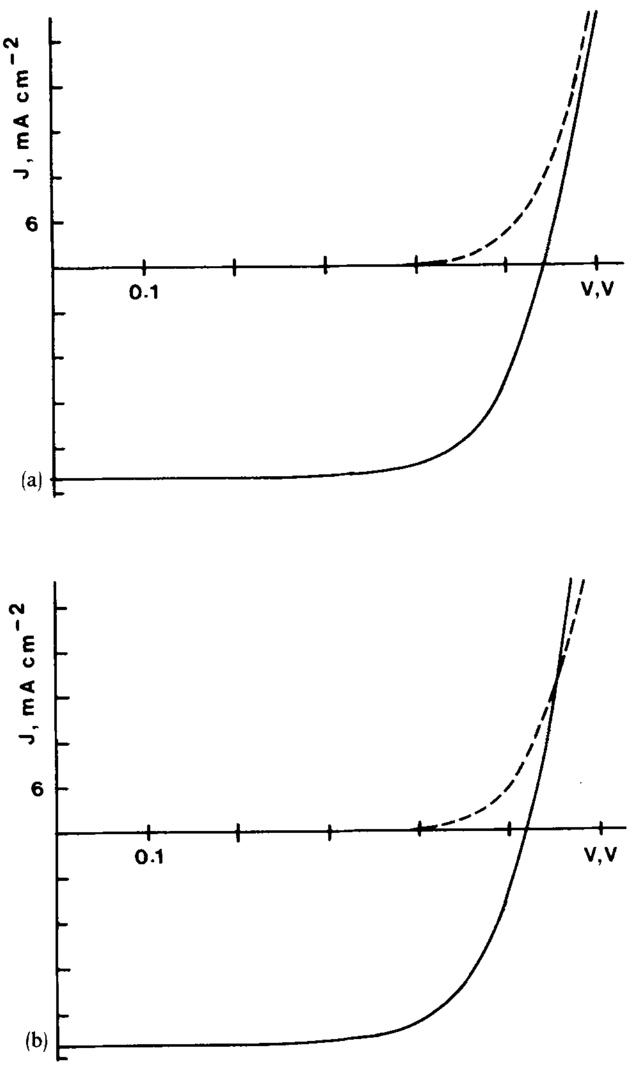

FIG. 2. Current voltage characteristics for typical inversion layer cells. The solid curves represent the illuminated characteristics, while the dashed curves represent the dark characteristics. (a) $<100>$ orientation, $\rho = 8\ \Omega$ cm, $V_{oc} = 540$ mV, $J_{SC} = 28.2$ mA. (b) $<111>$ orientation, $\rho = 13.5\ \Omega$ cm, $V_{oc} = 515$ mV, $J_{SC} = 28.2$ mA.

contribution from the inversion layer to the diode current should be rather small which is in agreement with the results reported in Ref. 9 where the dark saturation current $J_{0,\mathrm{dark}}$ for the $<100>$ inversion layer cell is found to be equal to that for a pure Al-SiO$_2$-pSi MIS solar cell with same orientation and resistivity and with an area equal to the contact hole area. Similar results have been found in this work when comparing the dark currents for $<111>$ inversion layer cells and pure MIS cells. So for the MIS inversion layer cell the dark current is found to be dominated by the current from the contact hole area and from the results in Refs. 6 and 9, the dark current should be dominated by majority carriers for this oxide thickness and given by

$$J_{\mathrm{dark}} = A^{*}T^{2}\exp\{-[2(2\,\mathrm{m}^{*})^{1/2}/\hbar]\chi^{1/2}\delta\}$$
$$\times\exp(-\phi_{\mathrm{ms}}/kT)[\exp(qV/kT)-1]. \qquad (5)$$

Here ϕ_{ms} is the effective metal to semiconductor barrier height, χ is the electron affinity of Si with respect to the oxide, and δ is the oxide thickness. Other notations are as usually defined. The area contributing to J_{dark} should be equal to the contact hole area, neglecting the contribution from the inversion layer.

For the illuminated cell the situation is quite different. Under illumination a high density of minority carriers is generated giving rise to the solar cell current. In general, negligible electric field exists in the p-type substrate of the cell, so that minority carrier electron current, $J_n(x)$ flows by diffusion only

$$J_n(x) \simeq q\,D_n\frac{dn(x)}{dx}. \qquad (6)$$

For the inversion layer (n side of the induced junction), electric field cannot be neglected. Thus the excess minority carrier hole current is given by

$$J_p(x) = -qD_p\frac{dp(x)}{dx} + q\mu_p\epsilon(x)p(x), \qquad (7)$$

where $\epsilon(x)$ is the electric field in the inversion layer. At the Si-SiO^2 interface, surface recombination takes place giving the boundary condition

$$J_p(0) = -J_{S,\mathrm{rec}} \approx -qSp_s.$$

For small forward voltages the electric field at the inversion layer will be so high that most of the generated holes will drift to the junction and contribute to the solar cell current. In this case p_s and thus $J_{S,\mathrm{rec}}$ will be small. For a high forward voltage such as $V = V_{oc}$, the electric field will be relatively small with the result that the values of p_s and $J_{S,\mathrm{rec}}$ will be rather high. So for increasing forward voltages an increasing number of the light generated minority holes will recombine at the Si-SiO$_2$ interface. This is also the case for the dark recombination current as seen from Eq. (4), but for the illuminated case the hole concentration and thus the surface recombination current will be very much higher.

For the illuminated cell the current is given by

$$J_{\mathrm{illum}} = J_0[\exp(qV/kT)-1] + J_{\mathrm{rec}} - J_{SC}, \qquad (8)$$

where the first current component represents the dark current, J_{SC} is the short circuit current, and the recombination current $J_{S,\mathrm{rec}}$ is a function of light intensity and forward bias.

From Eq. (6) the open circuit voltage is given by

$$V_{oc} = (kT/q)\ln[J_{SC} - J_{\mathrm{rec}}/J_0]. \qquad (9)$$

From Eq. (9) it is seen that V_{oc} decreases with increasing saturation current J_0 and increasing recombination current. When comparing the characteristics for different solar cells the result is

$$\Delta V_{oc} = \frac{kT}{q}\ln\frac{(J_{SC2} - J_{\mathrm{rec}2})J_{01}}{(J_{SC1} - J_{\mathrm{rec}1})J_{02}}. \qquad (10)$$

For the characteristics shown in Figs. 2(a) and (b) the measured short circuit current is the same, $J_{SC1} = J_{SC2} = 28.2$ mA, while there is a difference in open circuit voltage of $\Delta V_{oc} = 25$ mV. This difference is partly due to a difference in diode saturation current and partly due to a difference in recombination current. From the dark curves the voltages at $J = -J_{SC}$ is found to be $V_1(-J_{SC}) = 585$ mV and $V_2(-J_{SC}) = 572$ mV. So the ratio of J_{02}/J_{01} should be found from

$$V_2 - V_1 = (kT/q)\ln(J_{02}/J_{01}) = 13\text{ mV}. \qquad (11)$$

Using Eq. (11) in Eq. (10) the result is

$$\frac{kT}{q}\ln\frac{J_{SC2} - J_{\text{rec}2}}{J_{SC1} - J_{\text{rec}1}} = -12\text{ mV}. \qquad (12)$$

Now from the preceding discussion the recombination current is expected to be dominated by surface recombination. As J_{SC} is the same for the two cells, the surface concentrations of holes, p_s, is expected to be equal. So from Eqs. (2) and (3), the ratio of $J_{\text{rec}2}/J_{\text{rec}1}$ is given by

$$J_{\text{rec}2}/J_{\text{rec}1} = N_{ss2}/N_{ss1}, \qquad (13)$$

assumed that $\sigma_p\ v_{\text{th}}$ is the same for the two cells.

From literature [12,13] the ratio of the interface state densities for cells of $\langle 111\rangle$ and $\langle 100\rangle$ orientation is expected to be about $N_{ss}\ (111)/N_{ss}\ (100) = \frac{3}{1}$. Using this ratio for the recombination currents and inserting the measured value of J_{SC}, the result obtained from Eq. (12) is

$$J_{\text{rec}1} = 4{,}5\text{ mA}$$
$$J_{\text{rec}2} = 13{,}4\text{ mA}, \qquad (14)$$

showing that for the $\langle 111\rangle$ cell, the surface recombination current is near to half the short circuit current.

From the above discussion and results it is seen that the increase in the recombination current when going from dark to illuminated conditions is so high that the illuminated characteristics are rather different from what would be expected from the dark characteristics. This may be thought of as a special case of superposition breakdown, rather different from that described in Ref. 14, where the breakdown occurs as an increase in the depletion region recombination current. For the inversion layer cells the life times and mobilities are very high as the n layer is produced without diffusion of impurities, so the depletion region recombination current is very small which normally would indicate that the superposition principle is valid. This is also what would be expected from Figs. 2(a) and (b) where the illuminated currents are constant for a small forward bias below 0.2 V.

In conclusion the experimental data show that for Si inversion layer solar cells, the illuminated recombination current is highly dependent on the interface state density N_{ss} and for $\langle 111\rangle$ oriented cells, the magnitude of the recombination current is so high that it results in an appreciable reduction of the open circuit voltage V_{oc}. So in order to reduce the surface recombination current and to increase V_{oc}, the interface state density should be as small as possible.

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