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NEW METHOD FOR THE DETERMINATION OF THE SURFACE BARRIER HEIGHTS IN MIS TUNNEL DIODES (SOLAR CELLS)

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Abstract—The methods commonly applied for the determination of the surface barrier heights of Schottky diodes are usually extended for the MIS tunnel structures characterization, although, in such cases both, their range of application and accuracy are often strongly reduced.

In this paper a new photoelectric method for the determination of the surface barrier heights in MIS tunnel diode is proposed together with experimental results supporting its validity. The presence of the ultra-thin oxide layer between the metal and semiconductor does not reduce method's applicability as long as the direct semiconductor–metal tunneling is a dominant current flow mechanism through the oxide layer. In the contrary to the previous methods it allow us to measure directly the barrier height for minority carriers, and therefore, is especially recommended for minority carrier dievices.

1. INTRODUCTION

The surface barrier heights in MIS tunnel diode (Fig. 1) can be considered as ones of the most important parameters of such structures. They influence directly the current flow mechanism in tunnel devices and the open-circuit voltage of MIS solar cells.

Several methods for the barrier heights determination in metal-semiconductor contact have been worked out in the past [e.g. 1]. The same methods are often applied for the case of metal-insulator-semiconductor tunnel diodes [e.g. 2, 3], although it is well known, that in such structures they usually gives less accurate results.

A common method for measuring the barrier heights of Schottky diodes is based on the plotting the inverse of the square of device capacitance as a function of the gate voltage [1, 4, 5]. In MIS tunnel diodes, however, the application of this method can lead to less accurate results due to the presence of ultra-thin insulating layer separating the metal and semiconductor, and in some cases also due to the formation of the inversion layer at the semiconductor surface[5–7]. The other method [e.g. 1, 2], is based on the current-voltage characteristics of Schottky diodes. In such case the barrier height for majority carriers can be calculated from the value of the extrapolated saturation current. Unfortunately, the tunneling through the oxide considerably reduces the current of the MIS tunnel diode as compared to the Schottky diode. In consequence, this method can be applied in the former case only when the exact values of the effective dielectric thickness and semiconductor to oxide affinity are known. Furthermore, the above procedure, as well as the other method involving the Richardson plot I/T^2 vs $1/nT$ [e.g. 1–3] can not be applied for minority carrier devices, because minority carrier current is usually limited by generation-recombination-diffusion processes or tunneling[8, 9] and not by the thermonic emission. The direct measure of the surface barrier height can be also obtained from the threshold energy for photoexcitation of majority carriers into the semiconductor[1, 10]. However, this method again leads to inaccurate results since it does not take into account the effects of the barrier height lowering and photon-assisted tunneling[11–13].

In this paper the new method for the barrier height determination in MIS tunnel structures is developed both, theoretically and experimentally. It is believed that the proposed method is more accurate than previously used ones. In contrast to other methods listed above presence of the ultra-thin interfacial oxide do not reduce the accuracy of the method being proposed. Furthermore, the proposed method allow us to measure directly the barrier height for minority carrier devices such as some types of MIS solar cells.

2. THEORY

In Fig. 2 the energy band diagram of the illuminated Al–SiO$_x$–Si (p-type) tunnel diode is shown. Photoelectrical properties of such structure can be described by

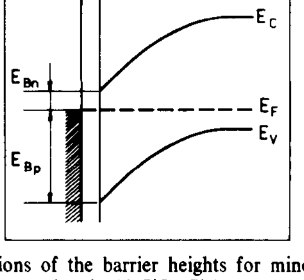

Fig. 1. Definitions of the barrier heights for minority $\bar{E}_{Bn}$ and majority E_{Bp} carriers in Al–SiO$_2$–Si (p-type) tunnel diode.

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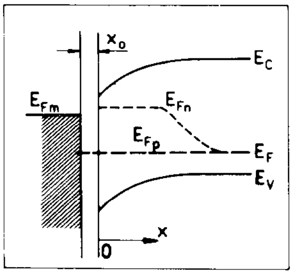

Fig. 2. Energy band diagram of illuminated Al-SiO_2-Si (p-type) MIS tunnel diode.

the set of following equations[8, 9, 15]:

$$I = I_{ph} - I_{RDO}[\exp(\Delta U_F/n) - 1] - I_{VTO}[\exp(-U_G) - 1] \tag{1}$$

$$I_{CTO}[\exp(\Delta U_p) - 1] = I_{ph} - I_{RDO}[\exp(\Delta U_F/n) - 1] \tag{2}$$

$$U_G = \Delta U_p - \Delta U_F \tag{3}$$

where I is the total MIS current, I_{ph} is the current of light generated carriers, U_G is the gate voltage in kT/q units, and where

$$\Delta U_F = [E_{Fn}(0) - E_{Fp}(0)]/\mathrm{kT} \tag{4a}$$

and

$$\Delta U_p = [E_{Fn}(0) - E_{Fm}]/\mathrm{kT}. \tag{4b}$$

Currents I_{CTO}, I_{VTO} and I_{RDO} in eqns (1, 2) stand for "zero currents" for electron tunneling, hole tunneling and generation-recombination-diffusion processes, respectively.

In general, currents I_{CTO}, I_{VTO} and I_{RDO} depend on the gate voltage and illumination intensity. For the gate voltage equal zero and under the weak illumination the I_{CTO}, I_{VTO} and I_{RDO} can be described as follows[14, 16, 17]:

$$I_{CTO} = A_c T^2 \exp(-\chi_c^{1/2} x_0) \exp(-E_{Bn}/\mathrm{kT}) \tag{5}$$

$$I_{VTO} = A_v T^2 \exp(-\chi_v^{1/2} x_0) \exp(-E_{Bp}/\mathrm{kT}) \tag{6}$$

where χ_c, χ_v = semiconductor to dielectric affinity for electrons and holes, respectively and A_c, A_v = Richardson constant for electrons and holes, respectively.

Furthermore, for zero gate voltage $U_G = 0$, eqns (1)–(3) can be reduced to the following form:

$$I_{sc} = I_{ph} - I_{RDO}[\exp(\Delta U_F/n) - 1] \tag{7}$$

$$I_{sc} = I_{CTO}[\exp(\Delta U_p) - 1] \tag{8}$$

$$\Delta U_p = \Delta U_F. \tag{9}$$

Differentiating now eqn (7) and eqn (8) the following equations are obtained:

$$\frac{\Delta I_{sc}}{\Delta I_{ph}} = 1 - I_{RDO}\exp(\Delta U_F/n)\frac{1}{n}\frac{\Delta U_F}{\Delta I_{ph}} - \left[\exp\left(\frac{\Delta U_F}{n}\right) - 1\right]\frac{\Delta I_{RDO}}{\Delta I_{ph}} \tag{10}$$

$$\frac{\Delta I_{sc}}{\Delta I_{ph}} = I_{CTO}\exp(\Delta U_F)\frac{\Delta U_F}{\Delta I_{ph}} + \left[\exp(\Delta U_F) - 1\right]\frac{\Delta I_{CTO}}{\Delta I_{ph}}. \tag{11}$$

Equations (10) and (11) can be transformed to the single relation, which at $I_{sc} = 0$ (when $\Delta U_p = \Delta U_F = 0$), can be simplified to the following form:

$$\left.\frac{\Delta I_{sc}}{\Delta I_{ph}}\right|_{U_G=0,\, I_{sc}=0} = \frac{1}{1 + \frac{I_{RDO}}{I_{CTO}}\frac{1}{n}}. \tag{12}$$

If the generation-recombination-diffusion current I_{RDO} is dominated by recombination processes (typical case for MIS structures on silicon at temperatures lower than 350–370 K), then:

$$I_{RDO} \cong q\frac{n_i}{2\tau_n}x_d \tag{13}$$

where q = electronic charge, n_i = carrier concentration in intrinsic semiconductor, τ_n = electron carrier lifetime in a p-type semiconductor and x_d = depletion region width.

Assuming additionally, that in these conditions the value of n in eqn (2) do not depend on temperature,† then, on the basis of eqns (5) and (13) the following relation can be written:

$$\frac{I_{RDO}}{I_{CTO}} \sim \frac{1}{\sqrt{T}}\exp[(-E_G/2 + E_{Bn})/\mathrm{kT}] \tag{14}$$

where E_G is the energy band gap.

Combining now eqn (12) and eqn (14) we obtain the following relation:

$$\left.\frac{1}{\Delta I_{sc}/\Delta I_{ph}}\right|_{U_G=0,\, I_{sc}=0} - 1 \sim T^{-1/2}\exp[(-E_G/2 + E_{Bn})/\mathrm{kT}]. \tag{14a}$$

It is easy to notice, that by the determination of the ratio $\Delta I_{sc}/\Delta I_{ph}$ for $I_{sc} = 0$ at various temperatures, and by ploting:

$$\ln\left[\left(\left.\frac{1}{\Delta I_{sc}/\Delta I_{ph}}\right|_{U_G=0,\, I_{sc}=0} - 1\right)T^{1/2}\right] \text{ vs } \frac{1}{T}$$

the barrier height for minority carriers E_{Bn} can be determined. Considering now the conditions, when diffusion processes are dominant, the current I_{RDO} can

†In fact, as temperature increases, the contribution of the diffusion current to the total I_{RDO} current also increases, which causes that the value of n decrease slightly. However, as long as recombination processes are much more efficient that diffusion processes, or when diffusion processes are much more efficient than recombination processes, this assumption is reasonable[17].

be written in the following form:

$$I_{RDO} \cong q\frac{n_i^2}{N_A}\sqrt{\left(\frac{D_n}{\tau_n}\right)} \tag{15}$$

where N_A = concentration of acceptor ions per unit volume and D_n = electron diffusion coefficient.

Assuming as previously, that in this conditions the value of n do not depend on temperature,† the following relation can be formulated:

$$\frac{I_{RDO}}{I_{CTO}} \sim T\exp\left[-(E_G - E_{Bn})/\mathrm{kT}\right]. \tag{16}$$

Combining eqn (12) and eqn (16) we obtain now the following relation:

$$\left.\frac{1}{\Delta I_{sc}/\Delta I_{ph}}\right|_{U_G=0,\, I_{sc}=0} - 1 \sim T\exp\left[-(E_G - E_{Bn})/\mathrm{kT}\right]. \tag{17}$$

Consequently, by the determination of the value $\Delta I_{sc}/\Delta I_{ph}$ for $I_{sc} = 0$ at various temperatures, and by ploting:

$$\ln\left[\left(\left.\frac{1}{\Delta I_{sc}/\Delta I_{ph}}\right|_{U_G=0,\, I_{sc}=0} - 1\right)T^{-1}\right] \text{ vs } \frac{1}{T}$$

the barrier height for minority carriers E_{Bn} can be determined, under the conditions when the diffusion processes are more efficient than recombination processes.

3. SAMPLE PREPARATION AND MEASURING SET-UP

In this study the MIS tunnel diodes were fabricated using ⟨100⟩ oriented, p-type, 2 Ω cm single-crystal silicon wafers. After the standard cleaning and etching procedure the ultra-thin oxide (20–30 Å thick) was grown on silicon by the d.c. plasma anodization[18]. The oxide thickness was measured by the ellipsometry. As a gate, the semitransparent vacuum evaporated aluminium about 100 Å thick was used. A heavy Al-layer was evaporated on the back side of the wafer to provide the ohmic contact.

The completed devices were mounted in the test fixture where the measurements could be performed at any temperature between 300 and 450 K with accuracy about 1 K. The illumination of $\lambda = 0.9\ \mu$m was provided by a CQYP 20 LED.

4. EXPERIMENTAL RESULTS AND DISCUSSION

For the determination of the barrier height on the basis of eqn (14), it is necessary to determine the $\Delta I_{sc}/\Delta I_{ph}$ ratio at various temperatures.

The first step in our experimental procedure was to measure the sets of I–V characteristics in the dark and under the illumination for several light intensities, at various temperaures. As an example, Fig. 3 and Fig. 4 show the sets of I–V characteristics in the dark and under the illumination at various temperatures. In these figures I_D and I_L stand for the current of the MIS diode in the dark and under the illumination, respectively. Figure 5 shows the $I_{LD} = I_L - I_D$ as a function of gate voltage V_G.

When MIS tunnel diode is reversely biased with gate voltage $V_G \gg \mathrm{kT/q}$ which results in $\Delta U_F \ll -1$, the dark

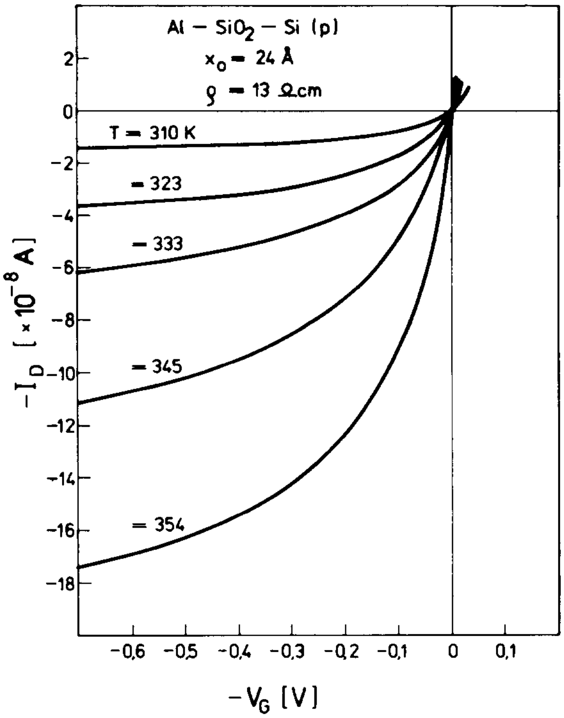

Fig. 3. I–V characteristics of the MIS tunnel diode taken in dark at various temperatures.

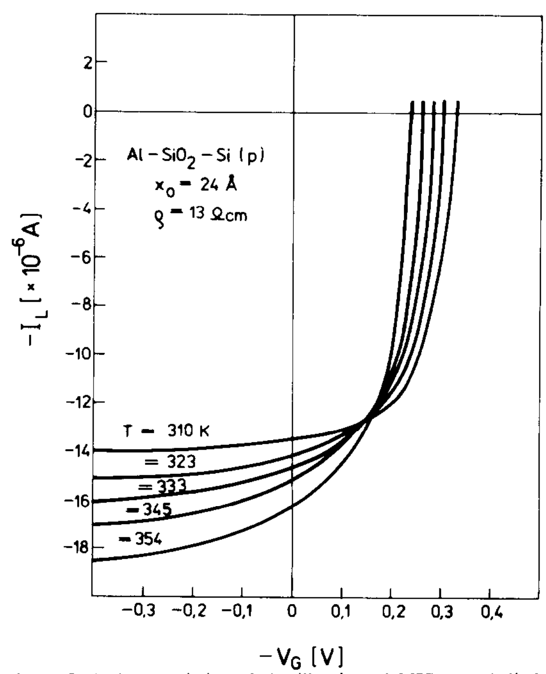

Fig. 4. I–V characteristics of the illuminated MIS tunnel diode taken at various temperatures.

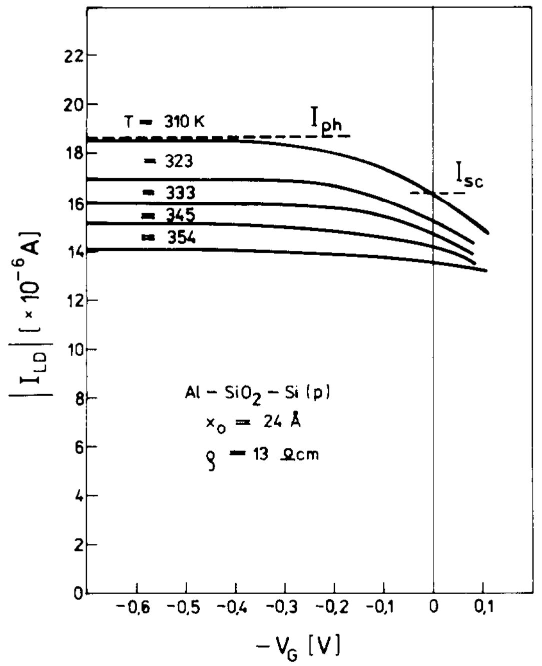

Fig. 5. Plot of the difference between current of illuminated and non-illuminated MIS tunnel diode vs gate voltage at various temperatures.

current, as we can see from eqn (1) can be expressed by

$$I_D\left(V_G \gg \frac{kT}{q}\right) = I_{RDO} + I_{VTO}.$$

Under the illumination and at the same gate voltage, the MIS current equals:

$$I_L\left(V_G \gg \frac{kT}{q}\right) = I_{ph} + I_{RDO} + I_{VTO}.$$

Thus, the value of I_{ph} can be determined as a difference between I_L and I_D currents for $V_G \gg (kT/q)$. The procedure for the I_{ph} determination is demonstrated in Fig. 5.

We have observed the current of light generated carriers I_{ph} increases with increasing temperature. This is a consequence of the lifetime of minority carriers and absorption coefficient increase with the increase of temperature[19–22]. On the other hand, the I_{sc}/I_{ph} ratio decreases considerably with increasing temperature. This in turn is due to the fact, that under the short circuit conditions, a displacement between the quasi-Fermi levels at the semiconductor surface occurs[23]. This displacement is as we can see from eqn (2) a driving force for the resultant minority carrier tunnel current. It also causes, that under the short-circuit conditions the generation-recombination-diffusion current I_{RDO} does not equals zero. As the temperature increases the I_{RDO} increase faster than I_{CTO}, and the I_{sc}/I_{ph} ratio decreases.

In our experiments, the curves I_{LD} vs V_G for $V_G \gg$ kT/q (Fig. 5) were usually so flat, that we had not difficulties with the determination of the I_{ph} value. This is a consequence of the fact, that for the wavelength $\lambda = 0.9\,\mu$m the charge carriers are generated in the semiconductor quasi-neutral region rather than in the space charge region. As a result, the current I_{ph} does not depend on the space charge region width and gate voltage. Measurements performed for several light intensities made it possible to notice that under experimental conditions applied in this study, the I_{ph} was directly proportional to the light intensity, and that the ratio I_{sc}/I_{ph} was almost independent on the light intensity. These effects are due to low value of the light intensity in this experiment. Under such conditions we have asumed, that:

$$\left.\frac{\Delta I_{sc}}{\Delta I_{ph}}\right|_{I_{sc}=0,\ V_G=0} \cong \frac{I_{sc}}{I_{ph}}.$$

The determination of the I_{sc}/I_{ph} ratio at various temperatures makes it possible now to evaluate the MIS barrier height by ploting ln $T^{1/2}(I_{ph}/I_{sc} - 1)$ vs $1/T$. Figure 6 illustrates such plot, and shows the band diagram of the semiconductor surface region resulting from this measuring procedure. As we can see from Fig. 6 in the examined device, the barrier height for minority carriers E_{Bn}, and for majority carriers $E_{Bp} = E_G - E_{Bn}$ equal 0.297 and 0.803 eV, respectively.

For various devices from the same experimental run we have obtained the E_{Bp} values ranging from 0.787 to 0.819 eV. In each case, these values were about 0.02 to 0.03 eV lower than the barrier heights calculated from the $1/c^2$ vs V plot, and 0.01 to 0.02 eV higher that those obtained from the Fowler plot. It is believed that the above differences are due to the effects discussed in the first section of this work.

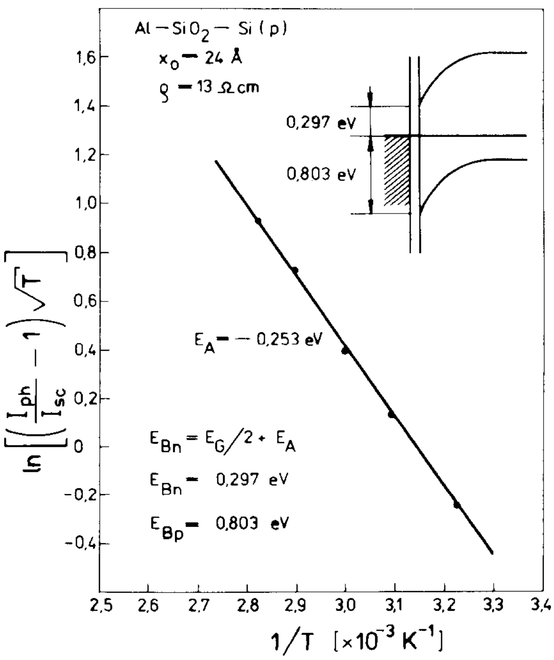

Fig. 6. The proposed procedure of the barrier height determination.

Considering the error of the proposed method, it appears that the error may arise from the presence of series resistance R_s of the MIS tunnel device. However, simple evaluation shows that for low values of I_{ph} and I_{sc} currents, this effect should be negligibly small. In typical MIS solar cells, as well as in our samples the value of R_s do not exceed few ohms. Even for the series resistance as high as $R_s = 100\,\Omega$ the voltage drop across R_s is 10^{-2} V and remains lower than kT/q. Another possible error of the proposed method is due to the neglecting of the diffusion or recombination processes, as well as the assumption that the value of n do not depend on temperature. This error, however, can be minimalized by choosing an appropriate range of temperature, and by proper interpretation of the measurement results, accordingly to eqn (14) or eqn (16).

Since eqns (5) and (6) are based on the assumption, that direct semiconductor-metal or metal-semiconductor tunneling is a dominant current-flow mechanism through the insulating layer, the proposed method may to some extend be restricted in structures with oxide thicker than about 50 Å. On the other hand, for oxide thickness of the order of a few angstroms, the I_{sc} may be very close to I_{ph}, and it may be difficult to notice the difference between them.

5. CONCLUSIONS

In this work a new method for the determination of the barrier height in MIS tunnel diode has been proposed together with the experimental results supporting its validity. Proposed method allow us to measure directly the barrier height for minority carriers, and therefore it seems to be especially useful for minority carrier MIS tunnel diodes. Presence of ultra-thin oxide do not reduce method accuracy as long as the direct semiconductor-metal tunneling is a dominant current flow mechanism trough the oxide layer.

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