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SCHOTTKY DIODES WITH HIGH SERIES RESISTANCE: A SIMPLE METHOD OF DETERMINING THE BARRIER HEIGHTS

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Abstract—The forward I–V characteristic of a Schottky diode is strongly affected by the series resistance. At low barriers and high resistances it is difficult to determine the diode parameters. I–V measurements at extremly low voltages enable the barrier height to be derived. In the case of indium tin oxide or palladium on a-Si:H, consistent results were obtained.

1. INTRODUCTION

Schottky barriers form an important part of most semiconductor devices; so it is of great interest to have easy methods of determining the barrier parameters (barrier height ϕ, ideality factor n, and Richardson constant A^*). One common way is to measure the forward current–voltage characteristic of the junction. Departing from the simple theory of either thermionic emission or diffusion[1,2], the current I is given by:

$$I = I_s(\exp[e(U - IR)/nkT] - 1) \tag{1}$$

with the voltage U applied to the sample. R denotes the series resistance and I_s the saturation current. The latter can be written as:

$$I_s = AA^*T^2\exp(-\phi/kT), \tag{2}$$

for thermionic emission limitation, and as:

$$I_s = AeN_c\mu F\exp(-\phi/kT), \tag{3}$$

for diffusion limitation, where A is the sample area, N_c the effective density of states in the conduction band, μ the carrier mobility, and F the strength of the electric field at the interface.

At a high series resistance or a low barrier height, it becomes difficult to obtain the different parameters. Additional problems arise in highly resistive conductors, as higher voltages involve carrier injection, the current then being no longer determined by an ohmic series resistance, but limited by space charge. This may lead to a pronounced decrease in bulk resistance[3]. With reference to Schottky diodes on a-Si:H, this has been discussed by Kanicki[4]. Here a plot of current vs applied voltage will deviate from a straight line at higher voltages. This can be taken into account by putting $R = R(I)$. An increase of resistance at low currents, as proposed by Manifacier and Henisch[5], can be ruled out, as the critical field is here much lower than the built-in field in Schottky diodes. Furthermore, the Richardson constant may deviate from its theoretical value by several orders of magnitude, as pointed out by Tam *et al.*[6].

One way to evaluate the diode parameters in spite of all these difficulties is pointed out by Norde[7]. This method has recently been modified by several investigators[8–12].

Our simple procedure to calculate the barrier height is based on the assumption that in both cases—thermionic emission and diffusion—limitation eqn (1) holds even for very low voltages. From the dependence of voltage on current:

$$U = \frac{nkT}{e}\ln\left(\frac{I}{I_s} + 1\right) + IR(I), \tag{4}$$

we derive the differential resistance:

$$\frac{dU}{dI} = \frac{nkT}{e(I + I_s)} + R(I) + I\frac{dR(I)}{dI}, \tag{5}$$

which is R_0 at zero bias:

$$\mathrm{R}_0 = \lim_{U\to 0}\frac{dU}{dI} = \frac{nkT}{eI_s} + R(I = 0) \tag{6}$$

As R_0 normally ranges from 10^8 to 10^{11} Ω, series resistances of up to several MΩ can be neglected. The barrier height is calculated from R_0 at different temperatures via an Arrhenius plot. The ideality factor n is used to fit eqn (1); it does not play any role for the final result as long as it will not vary very strongly with temperature.

2. EXPERIMENTAL

The samples were prepared as follows. Chromium bottom electrodes were evaporated on glass substrates. To provide an ohmic contact, they were covered with an 80 nm thick layer of hydrogenated amorphous silicon, doped by an addition of 1% PH_3 to the SiH_4. Then came a 1.1 μm thick undoped a-Si:H film, prepared at 220°C by the glow discharge

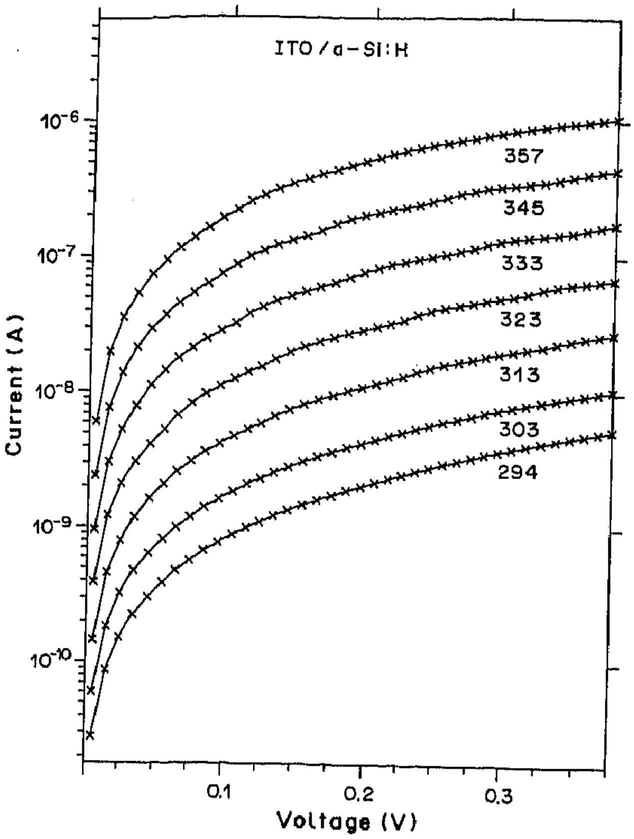

Fig. 1. Current–voltage characteristics of an ITO/a-Si:H junction at 294, 303, 313, 323, 333, 345 and 357 K.

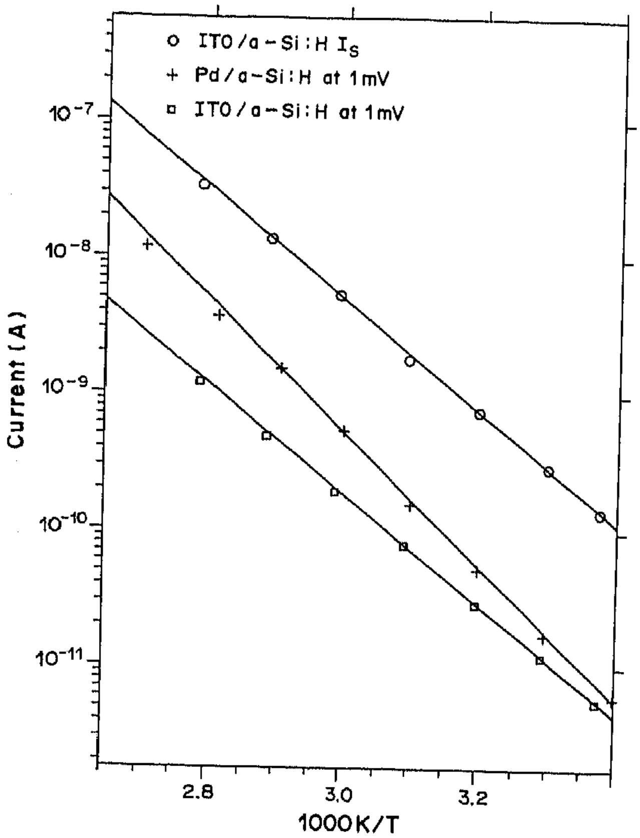

Fig. 2. Saturation current I_s and current I at 1 mV bias of an ITO/a-Si:H and a Pd/a-Si:H junction vs reciprocal temperature. The activation energies are 0.81, 0.80 and 0.97 eV, respectively.

of pure silane. On top, a 180 nm thick layer of indium tin oxide (ITO) was evaporated, forming Schottky contacts 20 mm^2 in size for investigation.

The measurements were carried out in a vacuum. A computer-controlled voltage source supplied the bias, and the current was measured by a Keithley picoamperemeter. So a series of current–voltage characteristics at different temperatures was obtained (Fig. 1).

3. DETERMINATION OF THE BARRIER HEIGHT

As the resistivity of the intrinsic a-Si:H is about $10^{10}\,\Omega$ cm, the series resistance amounts to several MΩ. Consequently, the plot of the logarithm of the current vs the applied voltage does not show any linear region, as can be seen from Fig. 1. Unfortunately, a linear plot of the I–V characteristic shows no linear behavior either, so that the series resistance cannot be evaluated.

We first tried to fit the I–V characteristics by the method indicated by Cibils[8], but it was very difficult to obtain an appropriate set of parameters Is, R and n. An Arrhenius plot of Is yields a straight line, which gives a barrier height of 0.81 eV (Fig. 2). Then we determined R_0 by measuring the current I at a voltage of 1 mV and plotted I in the same manner.

From the slope we obtained $\phi = 0.80$ eV in good agreement with the above result. This method is much easier to carry out, as it does not need any complicated fitting procedure. The only disadvantage is the need to measure very low currents at voltages of a few mV applied to the sample.

The method was also applied to an a-Si:H/Pd Schottky diode with a higher barrier. Our method and measurements of the internal photoemission (Fig. 3) both yielded the same barrier height of 0.97 eV in excellent agreement with the literature[13].

In our determination of ϕ, the factor nkT in eqn (6) was neglected because R_0 varied over several orders of magnitude, while the temperature was

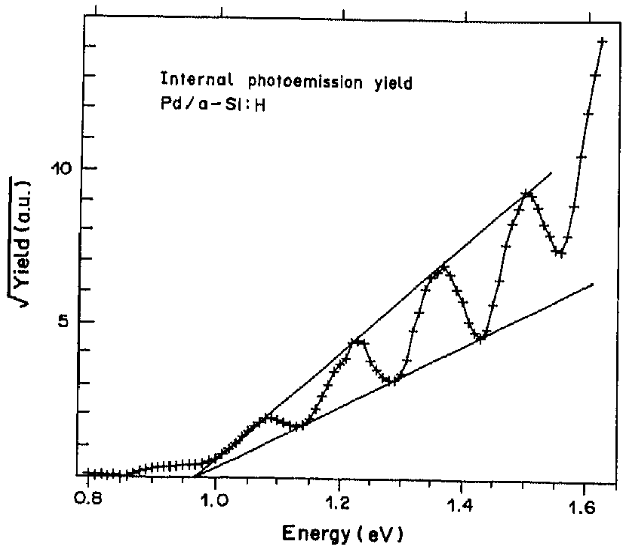

Fig. 3. Square root of internal photoemission yield vs energy. The barrier height deduced is 0.97 eV.

changed by less than a factor of 2. Furthermore, in some cases the ideality factor is an inverse function of temperature, which may result in a compensating effect[14].

A further topic is the dependence of the effective barrier height on applied voltage. The apparent decrease of ϕ is caused by a field-enhanced tunneling through the barrier, as pointed out by Jackson *et al.*[15]. Our method has the advantage that the measurement is carried out at almost zero bias. Hence the true barrier height is obtained.

4. CONCLUSIONS

We found a new method of determining Schottky barrier heights from $I-V$ characteristics even under difficult circumstances. The results are consistent with those obtained by other methods. For the first time we were able to investigate the barrier between ITO and a-Si:H, and to evaluate the barrier height of 0.8 eV. The result is very important for image sensor applications[16,17] and will be published in detail later[18].

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