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Role of Schottky-ohmic separation length on *dc* properties of Schottky diode

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The effect of Schottky-ohmic separation length on the barrier height, ideality factor and device series resistance of Al-*p*-Si Schottky barrier diodes in planar configuration have been studied. It has been found that the ideality factor and series resistance of the device vary nonlinearly with Schottky-ohmic separation length. The effect seems to be more pronounced on the series resistance, which has been attributed to recombination processes at the defect states and non-ohmicity at the ohmic contact of the device. The fitting of the experimental data confirms our previous observations of a logarithmic voltage dependence of the series resistance of the device.

Keywords: Planar Schottky barrier diode, Semiconductor surface potential, Barrier height, Ideality factor, Series resistance

1 Introduction

Metal-semiconductor contact or Schottky barrier diode is an extremely important device for their wide spread applications in the fields of microwave electronics, photovoltaics and in different other important semiconductor devices such as MESFETs, M-S-M devices and circuits such as Schottky clamped TTL circuits. In normal fabrication process, these devices are fabricated by depositing an appropriate metal at one side of the semiconductor for ohmic contact, while depositing a Schottky metal on the other side of the semiconductor. In the planar technology, however, the ohmic contact and Schottky contact are made at the same side of the semiconductor, which facilitate fabrication of a large number of devices and interconnections between the devices as may be required for the fabrication of integrated circuits. Accordingly, the planar technology has been found to be very useful in Schottky barrier diode fabrication process, as it offers various advantages over normal fabrication techniques. Several research works have been reported on Schottky barrier diodes fabricated applying planar technology to increase the breakdown voltage[1] or to achieve high cut-off frequency by reducing skin-effect parasitic resistance in microwave integrated circuits[2]. Even in optical sensor[3] or in ultraviolet detector fabrication[4] planar Schottky barrier diode has gained much attention. The fabrications of planar structures are found to be suitable for wafer level chip-scale package (WL-CSP) and also to achieve low capacitance in high frequency device applications[5].

Though the applications of planar Schottky barrier diode has gained numerous attention, the studies on the current transport process and its dependence on various device parameters in Schottky barrier diode structures in planar configuration are still a matter of concern. Parameters such as barrier height, ideality factor and mainly, the effect of series resistance in planar Schottky barrier diodes need to be examined more critically. A number of techniques are proposed earlier to extract series resistance of Schottky barrier diode. Norde[6] proposed a technique to extract the series resistance based on an auxiliary function, which was later found to be inappropriate to use for the diodes having ideality factor greater than 1. Several methods have been proposed to improvise the technique by modifying the auxiliary function[7-9] or applied[10] to find the series resistance of the device. But, these graphical methods may introduce inconveniences and uncertainties, leading to further refinement of Norde function. A more appropriate auxiliary function was proposed by Lee *et al.*[11]. The dependence of series resistance on bulk semiconductor thickness in the presence of interfacial layer was studied by Ayyildiz *et al.*[12].

It is,therefore, apparent that, though several works have already been published on the series resistance extraction process and its dependence on other device parameters, the applicability of such extraction processes in the case of Schottky barrier devices in planar configuration is still an important issue need to be addressed. Different methods normally opted for extraction of Schottky barrier diode parameters in vertical configuration might not work for planar devices, as it was already pointed out in our previous study[13] that the series resistance of a planar Al-*p*-Si Schottky barrier diode may be voltage dependent. The observed voltage dependence has been attributed to the existence of a potential barrier at the ohmic contact, which eventually transforms the device into a series combination of two diodes connected in back-to-back configuration. The above consideration has opened up further scope of research in finding other device parameters which have definite role on the voltage dependence of series resistance of the device in planar configuration. It would be interesting to investigate how the voltage dependence of series resistance of a planar Schottky barrier diode depends upon the physical separation between the ohmic contact and the Schottky contact. In the present work, an attempt has been made to study the above planar devices with the help of our recent evaluation scheme[13] and by systematically varying the Schottky-ohmic separation length of the device.

2 Experimental Details

A *p*-type Si wafer with a doping concentration 5×10^{15} cm^{-3} has been cleaned ultrasonically in distilled water, trichloroethylene, acetone and methanol and finally, dipped in hydrofluoric acid to remove inherent oxide layer on the surface of the sample. The samples are further rinsed in distilled water and dried and subsequently, loaded into a vacuum evaporation system for metallization. High purity aluminium was evaporated selectively at a pressure 2×10^{-5} mbar and heated under vacuum at 500°C for 30 min to establish an ohmic contact. A special mask has been fabricated to define Schottky contacts diagonally across the wafer such that the distance between the ohmic and Schottky contact varies for device to device. The inset in Fig. 1 shows the geometry and locations of Schottky and ohmic contacts on the surface of the semiconductor. The *dc* current-voltage measurements are made on each of these planar devices and the results are evaluated on the basis of current-voltage relation in the presence of a series resistance given by:

$$I = I_0 \exp[q(V - IR)/nkT] \qquad \dots (1)$$

where I_0 is the saturation current, R the series resistance, n the ideality factor of the device and other terms have their usual meanings. Eq. (1) allows determination of the series resistance numerically for the measured values of I and V. The series resistance extracted in this manner from the *I-V* data is critically analyzed.

3 Results and Discussion

The *dc* current-voltage characteristics of all the devices are shown in Fig. 1. The characteristics exhibit a linear rise of the logarithmic current followed by non-linearity at higher voltages. The linear regions of all the diodes are used to calculate the barrier height of the devices from the saturation current density of the device. The results hardly show any correlation between the measured values of the barrier height and Schottky-ohmic separation length despite of definite trends in the variation of diode current and ideality factor of the device. The observation has further been verified applying the evaluation scheme based on critical value of the semiconductor surface potential, which relate barrier height through other device parameters given by[14]:

$$\phi_{bp} = \Psi_s(J_c, V_c) + C_2 V_c + V_p - kT/q \qquad \dots (2)$$

where $\Psi_s(J_c,V_c)$ is the surface potential at a critical current density (J_c) and critical voltage (V_c), C_2 is the inverse of diode ideality factor and V_p is a measure of energy difference between the valence band and the Fermi level in the bulk of the semiconductor.

The variation of surface potential with applied voltage is shown in Fig. 2. From the plot, the critical voltage and surface potential values are extracted to estimate the barrier height of different planar Schottky barrier diodes. This method again corroborates our previous observation, by showing hardly any

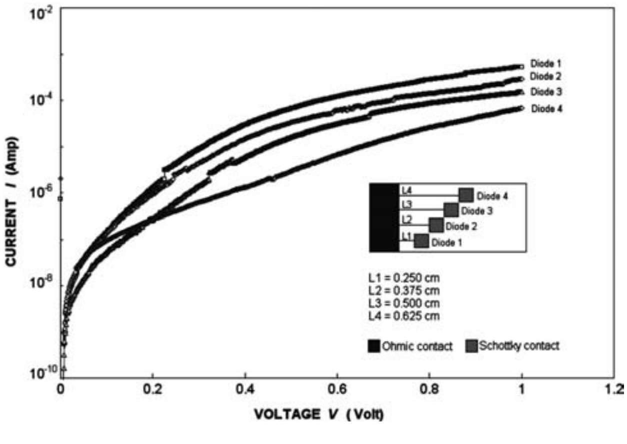

Fig. 1 — Measured current versus voltage characteristics of Al-p-Si planar Schottky barrier diodes. The inset shows the geometrical arrangement of the ohmic contact and Schottky contacts for all four diodes, fabricated diagonally on the wafer surface having different Schottky-ohmic separation lengths

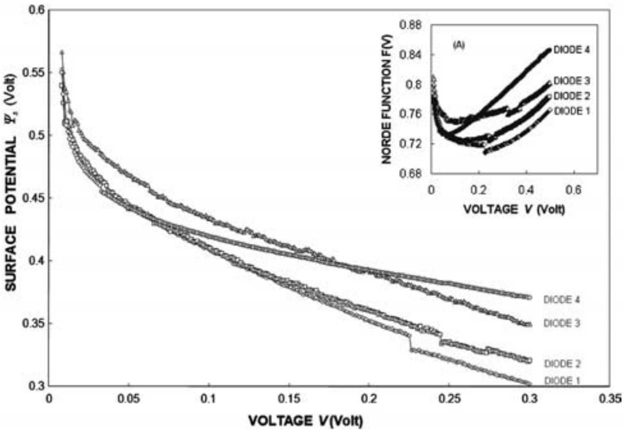

Fig. 2 — Surface potential versus voltage plots for the calculation of barrier height of Al-p-Si planar Schottky barrier diodes. The inset shows plot of Norde functions of the same group of planar diodes

Table 1 — Values of Schottky-ohmic separation lengths, saturation currents, ideality factors and barrier heights for fabricated Al-*p*-Si planar Schottky barrier diodes

Schottky-ohmic separation length (cm)	Saturation current I_0 (Amp)	Ideality Factor (n)	Barrier height ϕ_{bp} (calculated From I_0)	Barrier height ϕ_{bp} (calculated using Eq. 2)
0.25	1.6×10^{-8}	1.76	0.73	0.737
0.375	2.5×10^{-8}	2.13	0.72	0.74
0.5	1.1×10^{-8}	2.38	0.734	0.744
0.625	4.2×10^{-8}	4.29	0.707	0.716

correlation between the barrier height and Schottky-ohmic separation length. Table 1 presents the barrier height values extracted by conventional method and also by the technique using Eq. (2).

The linear regions of the *I*-*V* plots of the devices having different values of Schottky-ohmic separation lengths have been used to calculate the diode ideality factor using the familiar relation: $n = 1/(kT/q)\ \partial(\ln J)/\partial V$. The values of ideality factor are presented in Table 1 and its variation with the Schottky-ohmic separation length is shown in Fig. 3.

The image force barrier lowering (IFBL) of the devices were calculated for the fabricated planar diodes within the voltage range of 0.5 to –0.5 V. The calculated results show that, for a doping concentration of the order 10^{15} cm^{-3}, the values of IFBL are negligible for the diodes in present case. The maximum value of IFBL calculated for the diode nearest to the ohmic contact has been found to be 0.0135 V, whereas, its value for the far most diode has been found to be 0.0125 V, which is minimum among all the planar diodes examined in this work.

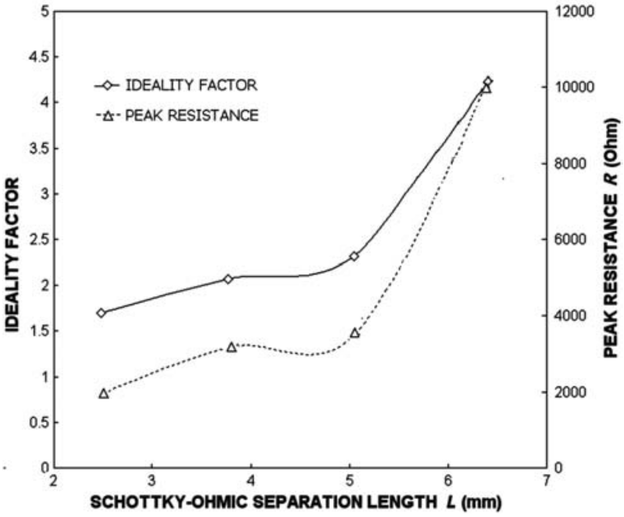

Fig. 3 — Variations of ideality factor and peak resistance of Al-p-Si planar Schottky barrier diodes as a function of Schottky-ohmic separation lengths

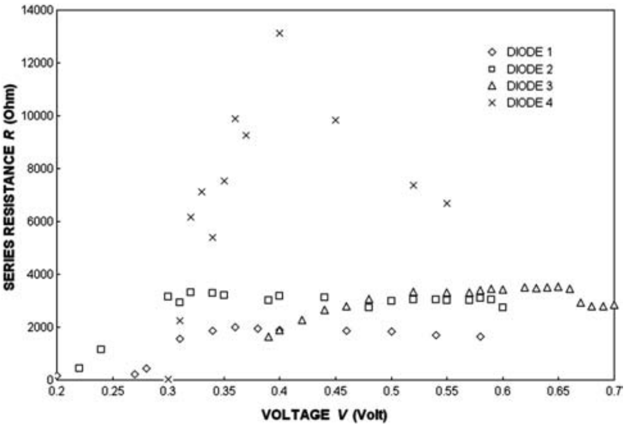

Fig. 4 — Voltage dependence of the series resistance of Al-p-Si planar Schottky barrier diodes determined numerically using the measured I-V data. The Schottky-ohmic separation lengths of the diodes are same as those referred to in Figure 1

The low values of IFBL suggest hardly any influence of IFBL on the extraction of other diode parameters.

To find the series resistance of the individual devices and determine its voltage dependence, we have followed our previous approach in which the series resistance has been estimated numerically from Eq. (1) for different sets of *I*-*V* data. Such a numerical evaluation reveals voltage dependence of the series resistance for all the diodes. The observed voltage dependence of the series resistance of the individual devices is shown in Fig. 4. It is seen that, the variation of series resistance with voltage is in general non-linear in nature, which exhibits a peak (may be defined as peak resistance) at a certain value of the

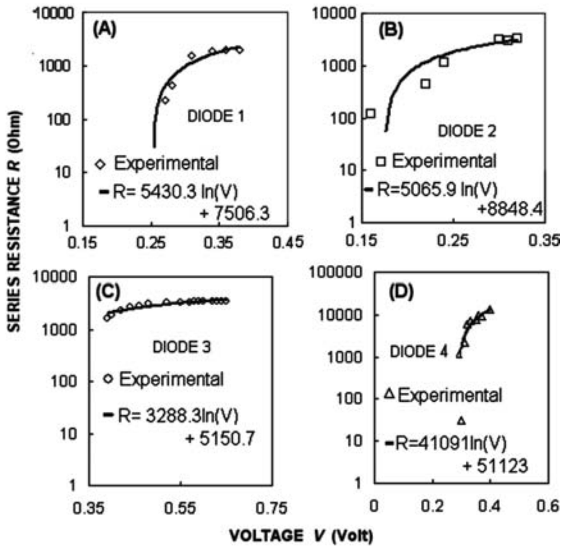

Fig. 5 — Voltage dependence of the series resistance of Al-p-Si planar Schottky barrier diodes before the appearance of resistance peak, observed at a specific bias voltage. The experimental data are fitted by the empirical relation $R=\gamma\ln(V)+C$, where γ and C are suitably defined constants. The fitted curves are shown by bold lines

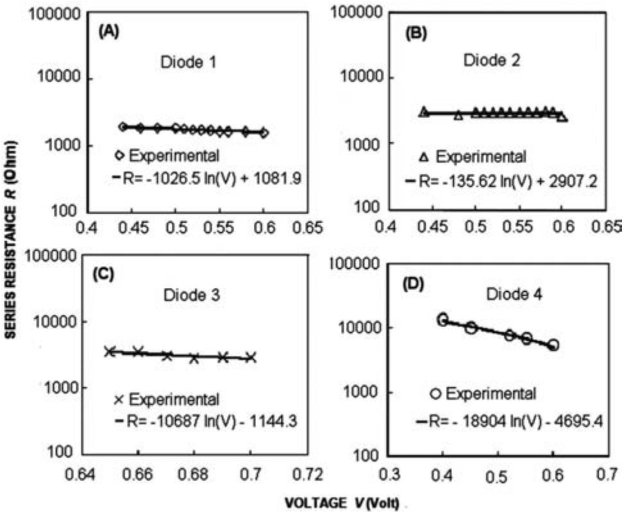

Fig. 6 — Voltage dependence of the series resistance of Al-p-Si planar Schottky barrier diodes after the appearance of resistance peak, observed at a specific bias voltage. The experimental data are fitted by the empirical relation $R=\gamma\ln(V)\pm C$, where γ and C are suitably defined constants. The fitted curves are shown by bold lines

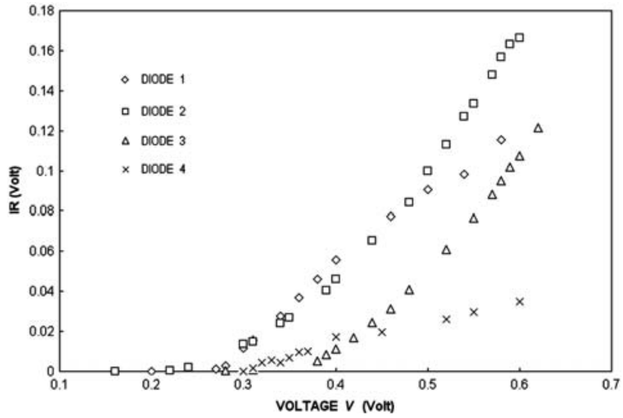

Fig. 7 — Variations of IR drop of different Al-p-Si planar Schottky barrier diodes as a function of applied voltage

bias voltage. The location of the peak position is determined by the device parameters. Fig. 4 shows the voltage dependence of the series resistance of diode number 4 having largest value of Schottky-ohmic separation length which has been found to be quite large as compared to all other diodes which seem to have a correlation with the Schottky-ohmic separation length as shown in Fig. 3. Interestingly, the nature of variation of peak resistance versus Schottky-ohmic separation length is very similar to that of the ideality factor.

To study further the voltage dependence of the series resistance, we have plotted in Figs 5 and 6, the extracted values of the series resistance before and after the appearance of the peak. The increasing trend in series resistance with bias voltage has been found to be in conformity with the previous finding of an empirical relation given by $R=\gamma\ln(V)+C$ where the parameters γ and C are suitably defined constants.

On the other hand, the decreasing behaviour of R beyond the resistance peak has been found to follow a functional form given by $R=\gamma\ln(V)\pm C$. The values of γ and C are found to be different before and after the appearance of a peak in the voltage dependence of series resistance.

The consequence of voltage dependence of the series resistance on the thermionic model can be readily examined by evaluating *IR* drop for the set of four diodes by noting *I* and *R* values at different voltages. The results of such evaluation are plotted in Fig. 7.

It is apparent from Fig. 7 that the *IR* voltage drop is insignificant at lower voltages. For example, the IR drops of only 0.012 V is obtained for diode 1 at a bias voltage 0.3 V, which may be considered to be a critical voltage below which the logarithmic *I-V* plot is almost linear down to the voltage $3kT/q$. Likewise, for the remaining diodes, the *I-V* characteristics are linear up to the respective critical voltages. Thus, under moderate doping over a voltage range from $3kT/q$ to the critical voltage, the well known thermionic theory can be applied[15-17]. However, above the critical voltage, the IR drop increases linearly with voltage. The variation is found to be much sharper for the diodes fabricated nearer to the ohmic contact.

The origin of the rising nature of R has been previously explained in terms of built-in barrier at the ohmic contact and drawing an analogy with the voltage behaviour of the series resistance of two diodes connected in back-to-back configuration. The same explanations hold for the present devices except for the effect of Schottky-ohmic separation length which has been found to be an additional parameter influencing the fitted relation. The decreasing nature of the series resistance on the other hand may steam from various well known effects such as field emission[15,16], minority carrier injection[18-20], Schottky effect (image force barrier lowering) or soft break-down at the ohmic contact. However, the voltage dependence of the series resistance of the diode having the largest value of Schottky-ohmic separation length, which has been found to be most significant amongst all the diodes inspite of lowest electric field, contradicts the occurrence of any of the above effects to be operational for the observed voltage behaviour of series resistance. We apprehend that the voltage dependence is a consequence of the presence of a barrier at the ohmic contact coupled with surface and bulk recombination processes determined by the density of recombination centers and the bulk resistance of the semiconductor associated with Schottky-ohmic separation length.

4 Conclusions

In conclusion, we have fabricated planar Schottky barrier diodes with varying Schottky-ohmic separation length. The analyses of the electrical characteristics reveal the barrier heights of the devices have hardly any correlation with the Schottky-ohmic separation length. However, the Schottky-ohmic separation length of the device has been found to have a definite role on the ideality factor and the series resistance of the device. The voltage dependence of the series resistance observed in these devices has been attributed to the non-ohmicity at the ohmic contact, which found to obey a logarithmic rule with the applied bias voltage.

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