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Temperature Dependence of Forward and Reverse Characteristics of Ti, W, Ta and Ni Schottky Diodes on 4H-SiC

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Abstract. In this study Ta, W, Ti, and Ni Schottky diodes are characterized under forward and reverse bias for temperatures between +21 °C and +200 °C. Additionally the Ti Diodes were characterized for temperatures between −168°C and +21°C. It will be shown that the reverse current is dominated by thermionic field emission for all metals, if the junction temperature is in the typical device operating temperature range. Furthermore we will show that non-ideal forward characteristics not necessarily have a negative influence on the reverse characteristics of the diodes. This will be explained by a model proposed by Tung, which considers the pinch off of the defects by the defect free areas around the defect.

Introduction

Schottky diodes on Silicon Carbide (SiC) are promising rectifiers for blocking voltages between 300 V and several kV mainly because of their fast switching capabilities. Although theoretical studies about the electrical behavior of Schottky contacts exist for some decades [1], the exact description of the forward and reverse characteristics is still an issue [2]. The leakage current of Schottky diodes on SiC is much higher than the leakage current predicted by the classical Schottky theory, which is typically used to describe Schottky diodes on silicon. For the design of SiC Schottky diodes it is crucial to be able to describe the reverse current by an adequate model, which will be presented in this work.

Experimental

The substrates used in this work were *n*-type 8° off-axis 4H-SiC supplied by Cree Research. A *n*-type 2.5 µm thick buffer layer and 8µm thick drift region were grown homoepitaxially on the substrates by a low pressure chemical vapor deposition process described elsewhere [3]. The net donor concentration of the drift region was between 5×10^{15} cm^{-3} and 9×10^{15} cm^{-3}. A 70 µm wide guard ring described by Mitlehner et al. [4] with an implanted Al concentration of 5.5×10^{17} cm^{-3} annealed at 1500 °C was used as an edge termination of the diodes. The Schottky metals with a thickness of 150 nm were deposited by sputtering. After defining the Schottky contact area of 1.54×10^{-2} cm^{-2} the diodes were annealed at 400°C for 4 hours. The electrical measurements above room temperature were done at wafer level and the measurements below room temperature were done with the diodes packaged in a TO220 case. With this punch-through design and a reverse bias of 600 V the maximum electrical field is only 3 % higher than in the non-punch-through (npt) case with the same drift layer doping concentration. Thus we assume that we have a npt design if we calculate the reverse current.

Results and Discussion

Forward characteristics. Ideally the forward characteristic of a Schottky diode is described by the equations

$$J = J_S \exp(V/nkT)(1-\exp(-V/kT) \quad \text{with } J_S = AT^2\exp(-\phi/kT)) \qquad (1,2)$$

with the bias V between the anode and cathode, the ideality factor n, the Boltzman constant k, the absolute temperature T, and the saturation current density J_S with the Richardson constant A, the elementary charge q, and the Schottky barrier height ϕ [1]. The barrier height and the Richardson constant can be determined experimentally by measuring the forward characteristics with the temperature as a parameter and fitting the theoretical curves to the measured characteristics as shown in Fig.1. By this method we determined the values listed in Tab. 1 for the different Schottky metals. For W ranges are given because this metal behaves very unstable and varied its barrier while the temperature was changed for the measurements.

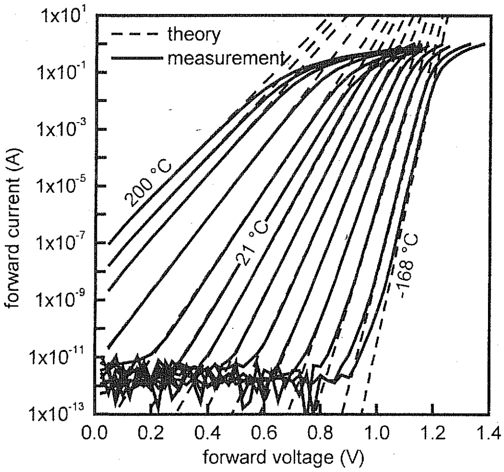

Fig. 1, Forward current of a Ti Schottky diode as a function of forward bias with the temperature as a parameter.

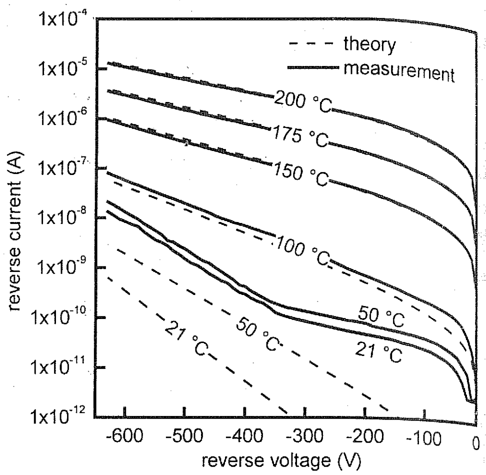

Fig. 2, Measured and calculated reverse characteristics of a Ti Schottky diode with the temperature as a parameter.

Modeling of the reverse current. The reverse current of Schottky diodes on silicon is normally described by the thermionic emission theory. This theory cannot explain the reverse behavior of Schottky diodes on SiC since the observed leakage current is much higher than the thermionic emission current. To describe the reverse current it has to be considered that the electrical field in a SiC device is much higher than in a comparable Silicon device. In our case the electrical field near the interface at 600 V reverse bias is around 1.35 MV/cm. At such high fields it seems likely that tunneling through the barrier has to be considered as dominating rather than thermionic emission.

Padovani and Stratton [5] proposed a model to describe the reverse current of Schottky diodes on highly doped, degenerated semiconductors considering field emission and thermionic field emission through the barrier. The thermionic field emission current can be expressed as

$$J = J_S \exp(V/E') \text{ with} \quad (3)$$

$$J_S = \frac{A\sqrt{\pi E_{00}}}{k}\sqrt{-V + \frac{\phi}{\cosh^2(E_{00}/kT)}}\exp(-V/E_0),\ E_0 = E_{00}\coth(E_{00}/kT), \quad (4a, 4b)$$

$$E_{00} = q\hbar\sqrt{N_d/(2\varepsilon)}\Big/\sqrt{2m^*},\ \text{and}\ E' = E_{00}[(E_{00}/kT) - \tanh(E_{00}/kT)]^{-1}, \quad (5a, 5b)$$

if the following condition is fulfilled:

$$1 - c_1 kT < kT\sqrt{2f_1} \text{ with } c_1 = 2\sqrt{\phi_b/(\phi_b - V)}\Big/E_{00},\ \text{and}\ f_1 = -\tfrac{1}{4}E_{00}V. \quad (6a, 6b, 6c)$$

m^* is the effective mass of an electron in the semiconductor, and ε is the dielectric constant of the semiconductor. If the temperature gets lower or the reverse bias gets higher this condition maybe not fulfilled and the current is dominated by pure field emission which can expressed as

$$J = \frac{AT\pi E_{00}\exp[-2\phi^{3/2}/3E_{00}(\phi - V)^{1/2}]}{k[\phi/(\phi - V)]^{1/2}\sin\{\pi kT[\phi/(\phi - V)]^{1/2}/E_{00}\}}. \quad (7)$$

With equation 6a it can be easily shown that field emission or thermionic field emission has to be considered for our diodes. Fig. 2 and Fig. 3 show the measured and calculated reverse current for the Ti and Ta Schottky diodes. The parameters used for the calculated currents are printed in Table 1. In the case of the Ti Diodes the measured and calculated thermionic field emission reverse current is nearly equal for temperatures of 100 °C and higher. For lower temperatures the model does not fit to the measurements and the reverse current is independent of the temperature as long as the thermionic field emission current is lower. Furthermore, we observed that the reverse current at room temperature varies within about two orders of magnitude and is also independent of the doping. This phenomenon is clear to see in Fig. 4 where the reverse current of 50 Ti diodes at –500 V is analyzed for two temperatures. At room temperature the reverse

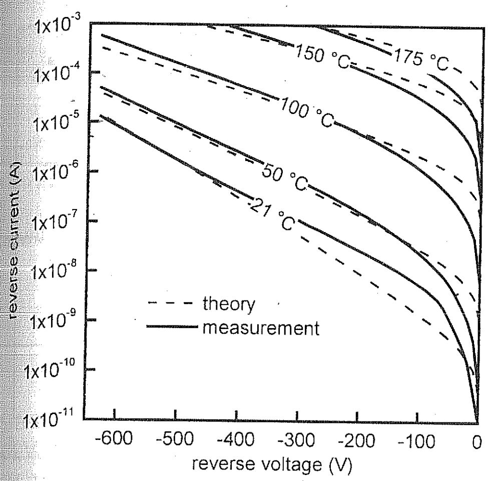

Fig. 3, Measured and calculated reverse characteristics of a Ta Schottky diode with the temperature as a parameter.

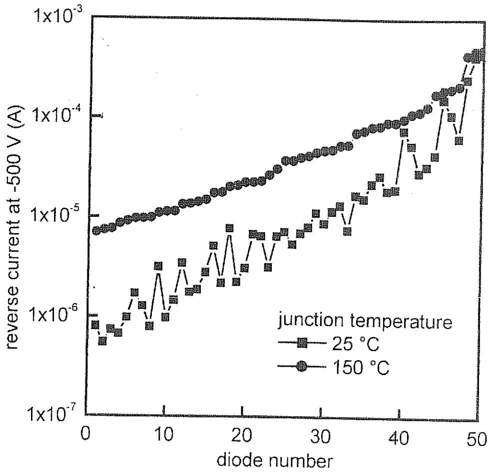

Fig. 4, Reverse current of 50 Ti diodes at -500 V with the temperature as a parameter. In this case the drift region was 4 μm thick with a doping concentration between 12×10^{15} cm^{-3} and 18×10^{15} cm^{-3}.

current varies about two orders of magnitude. At 150 °C the reverse current varies only about one order of magnitude which corresponds to the variation of the doping mentioned above. The origin of the reverse current at room temperature is not yet clear. But we can deduce from Fig. 2 that there are two mechanism leading to this current: one is dominating at moderate reverse voltages down from 0 V to −350 V (electrical fields below 1 MV/cm), the second one is dominating for higher reverse voltages.

In the case of the Ta diodes the calculated reverse current can be described by thermionic field emission for all considered temperatures since the reverse current is much higher due to the lower Schottky barrier. Similar results were also obtained for W. For the Ni diodes it was not possible to find reasonable parameters to describe the reverse current, which showed a very low temperature dependence. We think that the interface was not as perfect as for the other metals. This is indicated by the relatively high ideality factor of 1.10. To describe these measurements it may be necessary to introduce an interface layer. This will be subject of further work.

Metal	Forward Characteristics			Reverse Characteristics		
	ϕ [eV]	n	A [A/cm^{2}K^2]	ϕ [eV]	m*	A [A/cm^{2}K^2]
Ta	1.03	1.05	300	0.95	0.30	200
W	1.04 to 1.18	1.04	110 to 500	1.08 [1)]	0.19 [1)]	300 [1)]
Ti	1.27	1.05	400	1.27	0.22	200
Ni	1.40	1.10	150			

Table 1, Parameters extracted from the measurements of the forward and reverse characteristics at different temperatures. [1)] extracted only for one diode which had a stable Schottky barrier

Non-ideal forward characteristics and correlation with the reverse current? In contrast to the ideal forward characteristics it is also possible that the diodes show a non-ideal behavior as depicted in Fig. 5. This plot shows the measurements of diodes on a wafer which was intentionally processed in a way that produces a lot of defects, degenerating the forward characteristics. In the literature this behavior is described by local Schottky barrier height lowering e.g. caused by crystal defects or contamination enabling a higher current to flow over the barrier [2]. These areas with the lower barrier may also be preferred paths for the reverse current. To check this assumption we plotted the reverse current at 600 V as a function of the forward current at 0.3 V at room temperature in Fig. 6. In this plot all points right of the vertical line represent diodes that are affected by barrier height lowering down to 1 eV. The horizontal line represents the expected reverse thermionic field emission current for the same barrier height. In contrast to the first assumption the reverse currents of most of the diodes with a higher forward current (lower barrier) show nearly the same

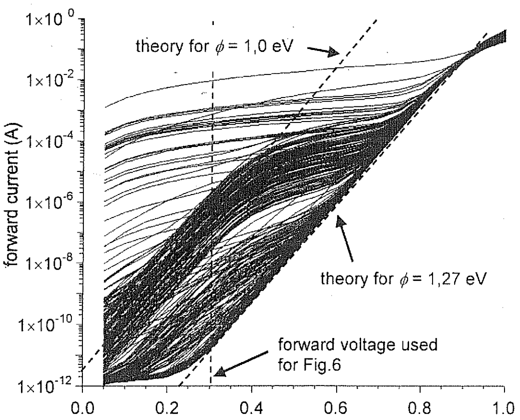

Fig. 5, Forward current as a function of forward bias with the temperature as a parameter for a Ti Schottky diode compared with the Schottky theory (dashed).

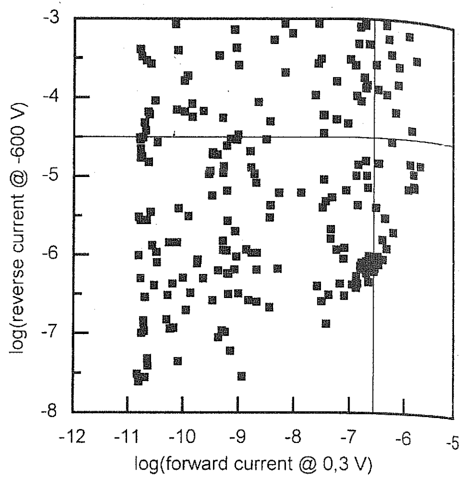

Fig. 6, Reverse current at –600 V as a function forward current at 0.3 V for Ti Schottky diodes on one wafer at room temperature. The lines are the theoretical values for a barrier of 1 eV.

reverse current as the diodes with an ideal forward characteristic. This behavior can be explained by a model proposed by Tung [6]. This model proposes that areas with a lower barrier which have smaller dimensions than the space charge region are effectively pinched off by the surrounding area with the higher barrier. This is comparable to the effect used in a merged pin Schottky rectifier where the area with the lower Schottky barrier is shielded by the area with the higher pn junction barrier [7]. Of course it is also possible that diodes with a relatively low forward current have a high reverse current, if the sum of the defective areas is relatively small but the size of the individual defects is to large to be shielded.

This leads to the conclusion that the reverse current cannot be described by a simple electrical equivalent circuit consisting of Schottky diodes with different barrier heights and areas in parallel. Such a model is only valid if the device quality is poor because of defects which are significantly larger than the space charge region. If the defects get smaller the modeling of the reverse current gets more complicated (see Tung [6]) or the reverse current is not affected significantly by such defects although the forward characteristics may be non-ideal.

Conclusion and Summary

It was shown that the reverse current of Schottky diodes on SiC can be described by the thermionic field emission theory in a wide temperature range and that the extracted barrier height is comparable to the barrier height extracted from the forward characteristics with the classical Schottky theory. The necessity of different values for the effective mass of the electrons is understandable because the effective mass at the interface may be different from the effective mass in the bulk of the semiconductor and furthermore may be influenced by the metal and its specific chemistry at the interface. It was also shown that defects at the interface which can be easily detected in the forward characteristic are not influencing the reverse current if they are small enough to be shielded by the defect free area around. This may be an explanation for the fact that it possible to produce Schottky diodes on SiC with a high yield although the density of crystal defects (e.g. stacking faults) is still very high in SiC substrates.

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