Electrical characterization of deep levels in N and P 6H-SiC Schottky diodes

N. SGHAIER, A. K. SOUIFI, J. M. BLUET, G. GUILLOT
Laboratoire de Physique de la Matière (UMR CNRS 5511), Institut National des Sciences Appliquées de Lyon, 20 avenue Albert Einstein, 69621 Villeurbanne cedex, France
E-Mail: nabil.sghaier@insa-lyon.fr

Excess current at low forward bias is observed for large-area Ni Schottky diodes on n- and p-type 6H-SiC. Random telegraph signal (RTS) measurements, carried out on these defective devices, show discrete time switching of the current. The trap signatures ($E_a = 0.35$ eV, $\sigma = 1.17 \times 10^{-18}$ cm$^2$ for n-type, $E_a = 0.43$ eV, $\sigma = 1.8 \times 10^{-20}$ cm$^2$ for p-type) extracted from deep level transient spectroscopy (DLTS) measurement are very close to those obtained from RTS. This strong correlation between the two different techniques is attributed to the presence of an extended defect which presents different charge states (i.e. an extended defect decorated by punctual traps). This assumption is reinforced by the DLTS measurements as a function of the filling time and as a function of the field.

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1. Introduction
Nowadays, a strong research activity is devoted to silicon carbide, mainly for the development of high power electronic devices. Indeed, because of its superior intrinsic electrical and physical properties (high electron drift velocity, high breakdown electric field, high thermal conductivity), SiC is a promising material to overcome the limit of silicon technology in this field [1]. For instance, Schottky rectifiers are quite attractive for power conversion applications requiring high breakdown voltage ($> 600$ V) and low on-resistance.

Nevertheless, even if promising demonstrators have been realized [2], the characteristics of large-area diodes still show high reverse current density in comparison to the thermionic emission theory [3] and excess in the forward current at low voltage [4, 5]. These phenomena have been interpreted in terms of barrier height inhomogeneities attributed to material quality deficiencies. Although the deleterious effect of micropipes (hollow-core screw dislocation) on the electrical performance of SiC devices has been well established [6], many other defects can be responsible for the high power device deficiencies [7]. This is why a detailed study of electrically active defects is necessary to understand the origin of non-ideal current–voltage characteristics.

In this paper we report $I$–$V$–$T$ analyses that reveal an excess current for low voltage. In a second section, we focus on these defective diodes in order to analyze the physical origin of the excess current. Toward this end, random telegraph signal (RTS) and deep level transient spectroscopy (DLTS) measurements have been performed.

2. $I$–$V$–$T$ characteristics
The Ni/6H-SiC Schottky diodes studied in this work were realized at the North Carolina State University on n- and p-type epilayers purchased from Cree Research. The layer thickness and doping level are, respectively, 1.2 $\mu$m and $N_d = 4.1 \times 10^{16}$ cm$^{-3}$ for n-type, and 1.6 $\mu$m and $N_d = 2 \times 10^{15}$ cm$^{-3}$ for p-type. Back-side ohmic contacts on n- and p-type were formed using, samples respectively, Ni and NiAl deposits annealed at 1000°C in a N$_2$ ambient. A circular Ni/SiC Schottky contact was next formed by electron beam evaporation through a Mo shadow mask after a short dip in HF in order to remove any oxide left on the SiC surface. The diode diameter ranged from 0.6 to 2.4 mm. The layer doping level and homogeneity through the layer has been checked by $C$–$V$. The results revealed that the doping profiles were homogenous and in agreement with nominal values.

$I$–$V$ characteristics were next measured in the temperature range 150–600 K showing important variation among the contacts for the same sample. Indeed, two different behaviors are observed:

1. For a few of the 0.6-mm diameter diodes, either on n- or p-type, quasi-ideal direct characteristics are obtained with an ideality factor of 1.1 at 500 K, typical of thermionic emission. Nevertheless, at room temperature and below, the ideality factor is closer to 2. This is due to a generation/recombination component of the current which vanishes with rising temperature.

2. For all the diodes with diameter greater than 0.6 mm (1.2 mm, 1.8 mm, 2.4 mm) an excess current for low forward voltage and in the reverse mode of operation is observed above 280 K. This kind of characteristic has
already been reported by different groups using different Schottky metallization [3–7]. Typically, we observe two exponential regimes, which can be modeled considering two different diodes in parallel with different barrier heights [4]. These two barrier heights correspond with the real Schottky for the upper (HBH) one, and with a localized defective zone at the metal/SiC interface for the lower one (LBH). Using this model to fit the $I–V$ curves, we have extracted the area ratio between the defective zone corresponding to the LBH and the rest of the diode with HBH. Typically, this ratio is about $10^{-5}$ at room temperature. For example, this corresponds to a defective zone of $3 \mu m^2$ for a 0.6-mm diameter diode. This value is consistent with the presence of extended defects (screw dislocations or micropipes) emerging at the surface.

In the following section we will focus on these defective diodes in order to determine precisely, the localization and the physical nature, of the defect responsible for the excess current.

3. Defects characterizations
3.1. RTS measurements
From the analysis of $I–V–T$ results presented above, it is clear that a localized current path, with smaller barrier height, corresponding to a defective area at the Ni/6H-SiC interface, is at the origin of the excess current. In these conditions, if a punctual trap is located in the neighborhood of the defective current path, the trapping/detrapping mechanism of an electron (a hole for p-type) will result in a discrete time fluctuation of the current. This phenomenon, called random telegraph signal (RTS), has been observed in silicon diodes and attributed to the presence of dislocations decorated by metallic impurities [8].

For all the diodes showing excess current in the forward $I–V$ characteristics, we have actually observed RTS for both n- and p-type samples. This RTS was noticed only above 280 K (when an excess current is present) and was not observed for the quasi-ideal diodes. For n-type, a combination of 2 to 4 RTS is frequently found at the same bias corresponding to different traps. We will see in Section 3.2 that three different signatures are also obtained in DLTS. In order to extract statistical parameters we have selected diodes showing a single RTS over the temperature range. Examples of these single time fluctuations of the current are given for the n- and p-type material in Fig. 1a and b, respectively. We clearly observe important current fluctuation with pulse time varying from 1 ms to 100 ms. According to the model of Hsu [9], the average pulse duration corresponding to high current values ($\tau_H$) and low current values ($\tau_L$), are, respectively determined by the capture ($\tau_c$) and emission time $\tau_e$ of an electron trap. The energetic position of the deep trap is then given by:

$$E_T = E_F + kT \ln \left( \frac{\tau_L}{\tau_c} \right)$$ (1)

Applying this model to n- and p-type material we have extracted the defect signature corresponding to the dominant current switching (i.e. the most frequently observed). The values of the activation energy and the cross-section are reported in Table 1. From these RTS measurements, we can conclude that individual defects channel the current through the layer. This result is consistent with two barrier height model proposed in Section 2.

3.2. DLTS measurements
To confirm the results obtained from RTS, DLTS measurement have been carried on the same diodes. Indeed, if punctual defects acting as trapping/detrapping centers located at the neighborhood of a defective current path are responsible of the RTS, we may also observe these deep defects in DLTS. Nevertheless, such a correlation between the two techniques has not been reported for silicon diodes. In our case, a DLTS signal is observed.

Typical spectra obtained for n- and p-type material are displayed in Figs 2a and b, respectively. For the n-type sample, three different peaks appear with a predominant one labeled peak 2. The shallower (peak 1) and deeper (peak 3) defects were observed only for a few diodes and with lower concentration than for the principal defect (peak 2). For the p-type sample, a single peak is observed. The traps signature extracted from the data of Fig. 2 are reported in Table 1 where they are compared to the values obtained from RTS. We clearly obtain a very good correlation between the two measurement techniques, which, to the best of our knowledge has never been reported before for SiC. This correlation implies that the...