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Correlation between barrier inhomogeneities of 4H-SiC 1 A/600 V Schottky rectifiers and deep-level defects revealed by DLTS and Laplace DLTS

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ABSTRACT

Electrical properties of commercial silicon carbide (SiC) Schottky rectifiers are investigated through the measurement and analysis of the forward current–voltage (*I–V*) and reverse capacitance–voltage (*C–V*) characteristics in a large temperature range. Some of devices show distinct discrepancies in specific ranges of their electrical characteristics, especially the excess current dominates at voltage <1 V and temperature <300 K. Standard deep level transient spectroscopy (DLTS) revealed the presence of a single deep-level defect with activation energy of about 0.3 eV, exhibiting the features characteristic for extended defects (e.g. dislocations), such as logarithmic capture kinetics. Furthermore, high-resolution Laplace DLTS showed that this deep level consists actually of three closely spaced levels with activation energies ranging from about 0.26 eV to 0.29 eV. A strong correlation between these two techniques implies that the revealed trap level is due to extended defects surrounded by point traps or clusters of defects. On the basis of obtained specific features of the deep-level defect, it was proposed that this defect is arguably responsible for the observed Schottky barrier inhomogeneities.

1. Introduction

Silicon carbide (SiC) is a well-known wide bandgap semiconductor material due to its extraordinary properties such as high reverse breakdown voltage, high electron velocity, high thermal conductivity and small dielectric constant [1]. As a result of these properties the most attractive applications of SiC-based devices are in the area of high power, high frequency and high temperature conditions [1,2], under which conventional semiconductors (Si, GaAs) cannot adequately work. The SiC Schottky barrier diodes (SBDs) are easy to fabricate and show high-switching-speed capabilities due to the absence of minority carrier injection effects observed in p–n junction devices [2]. Furthermore, wide bandgap and high breakdown field permit the operation of SiC Schottky diodes at much higher voltages (kV) and current densities (kA/cm^2) than it is possible with Si-based Schottky diodes.

There are many polytypes of SiC, but the technologically important ones are 3C-, 6H- and 4H-SiC, with the bandgap of 2.3 eV, 3.0 eV and 3.2 eV, respectively. 3C-SiC is the only form of SiC with a cubic crystal structure, while 4H- and 6H-SiC are only two of many possible SiC polytypes with hexagonal crystal structure [1]. In general, 3C-SiC is known as a low-temperature polytype, while 4H- and 6H-SiC are high temperature polytypes.

Despite the fact that in the last decade the SiC market is developing rapidly, there are still unresolved problems, especially dealing with the influence of electrically active defects on the performance and electrical characteristics of SiC-based devices. Besides the shallow dopants like nitrogen (N), aluminum (Al), phosphorus (P) or boron (B), which mainly govern the conductivity of SiC material, many intrinsic and extrinsic defect centers are usually present in SiC giving rise to energetically deep levels in the bandgap. These deep-level defects can act either as trapping centers for electrons and holes or recombination-generation centers limiting a lifetime of free charge carriers.

Since the early stage of SiC Schottky rectifier development, it has been observed that reverse leakage current density of large area diodes was always much higher (typically about 2 orders of magnitude) than expected by the thermionic emission theory [3,4] and the excess current was often observed in the forward characteristics at a low voltage, showing the anomalous behavior [5,6]. Non-ideal Schottky characteristics described above can be

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well explained using a Schottky barrier height (SBH) inhomogeneity concept, considered as two SBDs with different SBHs combined in parallel, according to the model given in [5,7]. In this model, the excess current at a low forward voltage results from low Schottky barrier height patches in localized regions, surrounded by a large area contact with higher SBH. It was also shown that lowering of SBH can lead to increasing of the reverse leakage current [3,7]. In order to eliminate the SBH inhomogeneities, many explanations were given so far, but most of them indicated the presence of defects, which result in lowering of the SBH in localized regions and thus indirectly influence on direct and reverse characteristics of SiC diodes [3–13]. The investigated defects include crystallographic defects (dislocations, micropipes, grain boundaries, stacking faults, etc.) and surface defects (carrots, comets, half-moons, growth pits, scratches, etc.) [4,7,10–12]. The micropipes are well documented defects in the literature that severely degrade the performance of SiC power devices [1,2]. It is also known that high density of screw dislocations can significantly deteriorate reverse characteristics at a critical value of the electric field limiting the breakdown voltage [4]. Until now, a great deal of efforts have been made to identify the source defects of SBH inhomogeneities. None of the known defects were claimed as a main factor controlling electrical properties of SiC. Therefore, the study of electrically active defects is of fundamental interest for the design and development of high quality modern SiC devices.

The deep level transient spectroscopy (DLTS) is widely used and sensitive method for studying deep-level defects in semiconductors [14]. It provides many electrical parameters of deep levels, such as activation energy (i.e. deep energy level position in the bandgap), capture cross section and defect concentration. Moreover, high-resolution Laplace DLTS technique (LDLTS) [15] is used for studying closely spaced deep levels with similar properties, because of its significantly improved spectral resolution compared to the standard DLTS.

In this paper, commercially available SiC Schottky rectifiers were studied by means of current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) characteristics as well as DLTS and Laplace DLTS techniques. The motivation of this work were results reported in Ref. [13]. It was discovered that some of the commercially available SiC Schottky rectifiers exhibit distinct discrepancies in specific ranges of the forward and reverse *I*–*V* characteristics. Especially, different values of reverse leakage currents occurred in most of the tested diodes, although these values were within the range guaranteed by a producer. According to literature data and own considerations, it was initially proposed [12] that such an extraordinary behavior may be evoked by the presence of electrically active deep-level defects in the bandgap. In order to verify this hypothesis we performed thorough *I*–*V* and *C*–*V* measurements in a wide range of temperature and tried to relate the observed discrepancies with deep-level defects existing in these devices.

2. Experiment

In this work, 4H-SiC Schottky barrier rectifiers produced by Cree Inc. were studied. The rectifiers CSD01060 (1 A, 600 V) have typical packages TO-220 and are used in switch mode power supplies, power factor correction and motor drives [16]. Current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) characteristics were measured within 80–380 K range by means of Keithley 2601A *I*–*V* sourcemeter and Boonton 7200 capacitance bridge, respectively. Standard DLTS measurements were performed within 77–400 K range with the use of DLS-82E spectrometer (SemiTrap), equipped with 1 MHz capacitance bridge meter and lock-in type integrator. For the high-resolution LDLTS measurements, samples were mounted in liquid nitrogen Janis VPF-475 cryostat, equipped with Lakeshore 331 temperature controller. Next, Boonton 7200 *C*–*V* meter was used for recording the capacitance transients, which were than analyzed by special numerical algorithms [15].

It is worth noting that the most confusing problem of this research is the fact that we do not know practically the area and kind of metallization used for preparation of the Schottky contact, as well as the type and doping level of the SiC material that are essential for proper analysis of electrical characteristics and calculation of diode parameters. The only true information is that 4H-SiC polytype was used for preparation of the investigated Schottky rectifiers (information received from personal communication with CREE Inc. representatives). Nevertheless, assuming a diameter of the contact area equal to 0.5 mm^2, which in our opinion is close to the typical values for SiC Schottky diodes, we obtained electrical parameters (especially SBHs) close to the observed typically for many 4H-SiC Schottky barrier rectifiers with different metallization's [4–7,9,10,17].

3. Results and discussion

3.1. I–V–T and C–V–T measurements

Rectifying properties of four commercial 4H-SiC Schottky barrier diodes were studied by means of *I*–*V* method [13]. Standard approach, based on the thermionic emission theory was used to describe a current flow across the Schottky barrier interface [18]:

$$I = I_S\left[\exp\left(\frac{q(V - IR_S)}{nkT}\right) - 1\right], \tag{1}$$

with the saturation current I_S defined by

$$I_S = AA^*T^2\exp\left(-\frac{q\Phi_{b0}}{kT}\right), \tag{2}$$

where n denotes the ideality factor, R_S is the series resistance, q is the elementary electron charge, k is the Boltzmann constant, T is the temperature, A denotes the diode area, Φ_{b0} is the Schottky barrier height and A^* is the Richardson's constant, previously calculated and equal to about 146 A/cm^2 K^2 for 4H-SiC [17].

The investigated diodes are intended to work with a maximum forward current of 1 A and maximum reverse voltage of 600 V. Measured characteristics of four diodes at a room temperature were generally in accordance with the characteristics presented in product data sheets [16]. In a forward current range, where the diodes are intended to work, that is for current from 1 mA to 1 A, the *I*–*V* characteristics of all measured diodes were almost identical. The calculated series resistance at a nominal current of 1 A is about of 0.45 Ω and the ideality factor ranges from about 1.12 to about 1.17. However, there were very different values of reverse leakage currents, although these values were within the range guaranteed by the producer. On the other hand, the room temperature forward *I*–*V* characteristics below the voltage of 0.75 V and the reverse *I*–*V* characteristics below the voltage of 600 V showed large discrepancies, as reported in [13]. Fig. 1 shows representative *I*–*V* characteristics in a semi-logarithmic plot for one of the studied diodes at several temperatures within the range from 80 K up to 380 K and with the step of 20 K. As one can recognize, the presented characteristics are not ideal, because they show one or even two distinct "knees". At higher temperatures (>300 K) the characteristics are similar as those for ideal Schottky rectifiers, yielding the value of the ideality factor (extracted from the linear part of the plot) close to one, indicating that thermionic emission mechanism is responsible for the current transport through the Schottky junction. According to the thermionic emission theory [18] of Schottky barrier diode for a forward bias, the log(*I*)–lin(*V*) plot should be a straight line extending over many orders up to a