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Electrically active defects in SiC Schottky barrier diodes*

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The electrical properties of deep-level defects in real packaged SiC Schottky barrier rectifiers were studied by deep level transient spectroscopy (DLTS). One deep-level trap with an activation energy in the 0.29-0.30 eV range was revealed to be present in all the tested samples. The electrical characteristics of the trap indicate it is probably attributed to dislocations or to metastable defects, which can be responsible for discrepancies observed in I-V characteristics (see Ref. [2]).

Keywords: *SiC, Schottky diode, deep-level defect, DLTS.*

1. Introduction

Silicon carbide (SiC) is still one of the most attractive wide bandgap materials having many applications in the field of microelectronics and optoelectronics. The tremendous properties of SiC-based semiconductor electronic devices, such as large breakdown electric field, high electron mobility and saturation electron velocity, high thermal conductivity together with good thermal stability render this material suitable for use in high-temperature, high-power, and/or high-radiation conditions under which the conventional semiconductors (Si, GaAs) cannot work properly [1].

Among the many different polytypes of SiC, only two of them, 4H-SiC and 6H-SiC, having hexagonal crystal structure, are commercially available. Owing to the different arrangement of the Si and C atoms within the SiC crystal lattice, each polytype exhibits unique, fundamental electrical and optical properties, which are utilized in the fabrication of modern electronic and optoelectronic devices (e.g. green and blue LEDs, photodetectors, rectifiers, thyristors, transistors, etc.). Some of the more important material properties of 4H- and 6H-SiC are listed in Table 1, and are compared with the parameters for the conventional semiconductors Si and GaAs.

In comparison with common Si and GaAs wafer standards, presently accessible 4H- and 6H-SiC wafers are generally small, expensive and of inferior quality. Nevertheless, most SiC electronic devices are fabricated as much higher quality epitaxial SiC layers grown on the top of the wafer. The prototype SiC devices deliver excellent area-normalized performance, often more than 10 times better than the theoretical power density of Si power electronics. Unfortunately, nowadays there are many observable defects present in state-of-the-art SiC homoepitaxial layers, which have prevented the scale-up of small area prototypes into large area prototypes capable of delivering high operating currents [1, 2].

In addition to the high densities of crystalline defects, such as hollow-core screw dislocations (micropipes) and closed-core screw dislocations, the surface morphologies of commercial SiC wafers also exhibit many undesirable features, such

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Table 1. Comparison of selected semiconductor properties of 4H- and 6H-SiC with Si and GaAs at 300 K [1].

Property	**4H-SiC**	**6H-SiC**	**Si**	**GaAs**
Bandgap energy [eV]	3.2	3.0	1.1	1.42
Breakdown electric field [MV/cm]	3.0	3.2	0.6	0.6
Saturated electron velocity [cm/s]	2.0	2.0	1.0	1.2
Electron mobility [cm^2/Vs]	800	400	1200	6500
Hole mobility [cm^2/Vs]	115	90	420	320
Thermal conductivity [W/Kcm]	5.0	5.0	1.5	0.5
Relative dielectric constant	9.7	9.7	11.9	13.1

Table 2. Main electrical characteristics of SiC Schottky diodes CSD01060.

Parameter	**Typ.**	**Max.**
Repetitive Peak Reverse Voltage [V]		600
Forward Voltage [V], I_F=1 A, T_J=25 °C	1.6	1.8
Repetitive Peak Forward Surge Current [A], T_C=25 °C		7
Average Forward Current [A], T_C=150 °C		1.4
Reverse Current [μA], V_R=600 V, T_J=25 °C	20	100
Power Dissipation [W], T_C=25 °C		21.4
Total Capacitance [pF], V_R=0 V, T_J=25 °C, f=1 MHz	80	
Operating Junction Temperature [°C]		175

as "grow pits", "triangular inclusions" or "step bunching", which could affect SiC device processing and operational performance [1]. In particular, a micropipe defect is regarded as the most damaging "device killer" defect in SiC electronics.

For example, rectifying power devices fail at micropipe defects, leading to undesired localized current flow through micropipes at electric fields far below the critical reverse-breakdown field of defect-free SiC. Over the last decade, significant efforts by SiC material vendors have succeeded in reducing micropipe densities by over a 100-fold, resulting in higher device operating currents. However, there are still very high densities of other less-harmful dislocation defects, which are believed to be responsible for a variety of non-ideal device characteristics that have hindered the reproducibility and commercialization of some SiC electronic devices [1].

In this paper, we used deep level transient spectroscopy (DLTS) [3] to investigate the electrical properties of deep levels related to defects identified in commercially available SiC Schottky barrier rectifiers. The motivation for this work were the results reported by Z. Synowiec [2], where direct current characteristics of the diodes were presented and discussed. The presence of the defects evoked large discrepancies in specific ranges of the forward and reverse I-V characteristics. In particular, different values of reverse leakage currents occurred in most of the tested diodes, although these values are within the range guaranteed by the producer. The author [2] proposed that reverse leakage current differences can be evoked by defect-assisted tunneling through the Schottky barrier.

2. Experiment

The DLTS experiments were performed on four SiC Schottky barrier rectifiers manufactured by Cree Inc. The CSD01060 rectifiers have typical packages TO-220-2 and are intended for applications including switch mode power supplies, power factor correction and motor drives. The main

electrical characteristics taken from the Cree data sheets for these diodes are given in Table 2.

The measurements were performed within the 100–240 K temperature range, with the aid of a DLS-82E spectrometer (Semitrap), equipped with a 1 MHz capacitance bridge meter and lock-in type integrator [4]. A bath-type liquid nitrogen cryostat enabled us to change the sample temperature from 80 up to 450 K.

3. Results and discussion

Exemplary DLTS temperature spectra for the four tested diodes, labelled A, B, C and D are presented in Fig. 1. The measurement conditions were as follows: quiescent reverse bias (U_R) of -6 V, forward filling-pulse height (U_P) of 0 V, filling-pulse width (t_p) of 50 μs and the lock-in frequency (f_0) equals to 50 Hz. The one dominant deep-level trap, called T1, was revealed at around 150 K, for all the investigated samples. As one can see, under the same measurement conditions, trap T1 differs in concentration (DLTS-signal amplitude), being significantly larger for diodes A and B compared with samples C and D.

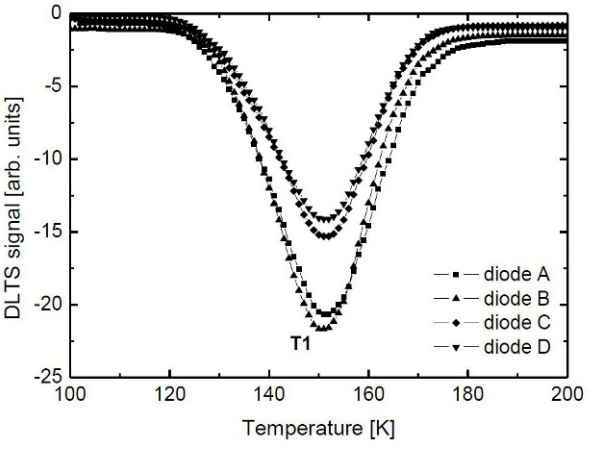

Fig. 1. DLTS spectra of the real SiC Schottky diodes measured at the temperature range from 100 K to 200 K. Reverse bias U_R = -6 V, filling pulse height U_p = 0 V, lock-in frequency f_0 = 50 Hz, width of the pulse (t_p) equal to 50 μs.

In order to determine the thermal activation energy (E_t), and the capture cross section ($\sigma_{n,p}$) of the T1 trap, the temperature scans for several lock-in frequencies were measured. In Fig. 2 exemplary DLTS spectra for diode A (Fig. 2a), diode B (Fig. 2b), diode C (Fig. 2c) and diode D (Fig. 2d) are shown. They enable construction of the Arrhenius plots of $e_{n,p}/T^2$ as a function of reciprocal temperature $1000/T$, which are shown in the insets of Fig. 2. By performing a standard least-squares data fit, the activation energies of the T1 trap were determined from the Arrhenius plots, and were found to be in the range from 0.29 eV to 0.3 eV, and the capture cross sections were found to be of order 10-15 cm^2 for diodes A, B, C and D, respectively.

One of the most important features of the T1 trap, discovered in our experiments, is shown in Fig. 3. The DLTS spectra, recorded at about 2.5 Hz lock-in frequency and quiescent bias conditions: U_R=-6 V, U_P=0 V, are shown for different widths of the filling-pulse times. It is noticeable that, for the T1 trap, the DLTS-signal does not achieve a distinct saturation for longest filling-pulse times, for all the investigated diodes, which is characteristic for noninteracting isolated point defects or impurities [5]. However, it increases consistently as the width of the pulse increases, which is representative of quasi-linear dependence.

There are probably two possible reasons for a deep-level defect to exhibit such DLTS-line behaviour. First, we can assume that the T1 deep-level traps are not arbitrarily distributed within the SiC crystal, but are concentrated in the vicinity of the extended defect (dislocation). In that case, if a decorated extended defect or a dislocation is present, the interaction between individual energy levels results in repulsive electrostatic potential, built up at the defect, which limits the subsequent capture of carriers [6, 7]. This phenomenon implies the capture kinetics of the traps are logarithmic, manifesting itself in the DLTS measurements, in the linear dependence of the DLTS-peak amplitude on the logarithm of the filling-pulse duration [7]. In contradistinction, isolated point defects or impurities typically have exponential capture kinetics [8]. It is generally considered as a principal argument for ascribing the traps either to point defects or dislocations decorated with point defects or else the

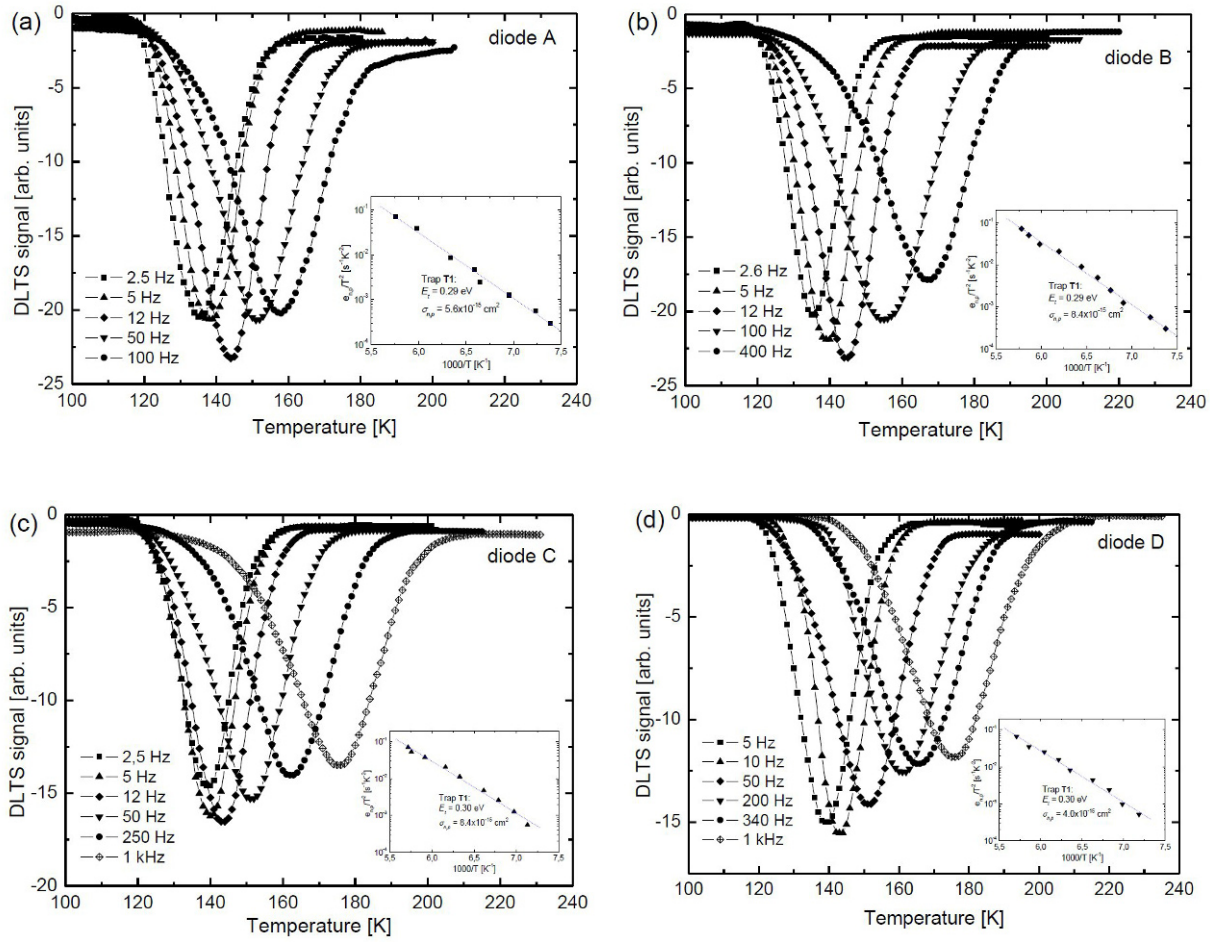

Fig. 2. DLTS temperature spectra of the diodes A (a), B (b), C (c) and D (d) measured for several lock-in frequencies, within 100-240 K temperature range. Reverse bias U_R = -6 V, filling pulse height U_p = 0 V, width of the pulse (t_p) equal to 50 μs. In the insets Arrhenius plots are shown for deep-level trap T1 observed in all the diodes.

dislocation core itself. As shown in the insets of Fig. 3, the T1 trap peak amplitude has a quasi-linear dependence on the logarithm of the filling-pulse time, suggesting the trap is probably due to dislocations. The existence of an extended defect decorated with point traps was previously observed in 6H-SiC Schottky diodes [9].

The second reason for such behaviour is that the DLTS-peak saturating for a very high filling-pulse time could be a fingerprint for a thermally activated capture cross section for the T1 trap [10], which is typical for metastable defects, such as DX centers frequently observed in CdMnTe or AlGaAs [11, 12]. The characteristic feature of a DX center is the presence of a thermal capture barrier which impedes the defect from returning from the metastable excited state to the ground state. The metastable defects were also previously observed in 4H- or 6H-SiC [13, 14].

In order to identify the exact nature of the T1 trap we need more experiments, which can help us to distinguish between these two possible origins for the related trap. Most especially, the measurement data for the relationship between the electric field and the emission rate might explain some of the discrepancies between the current characteristics observed for the tested diodes in the previous paper [2]. As the electric field strength increases, the DLTS-peak should shift towards lower temperatures, which results in a lowering of the Schot-

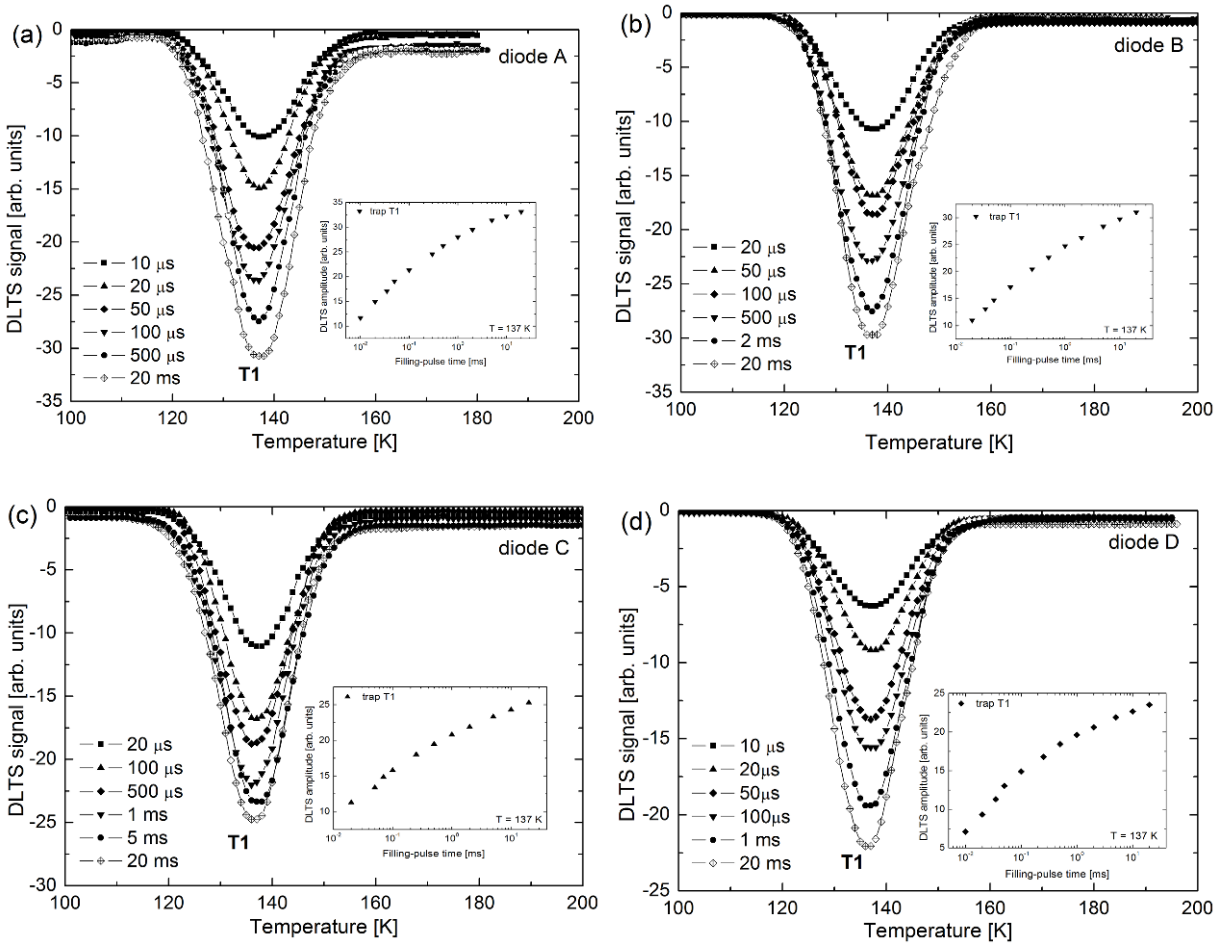

Fig. 3. DLTS spectra of the diodes A (a), B (b), C (c) and D (d) measured for different filling-pulse times and constant lock-in frequency equal to 2.5 Hz (reverse bias U_R = -6 V, filling pulse height U_p = 0 V). The insets show DLTS-peak amplitude of the T1 trap vs filling-pulse time.

tky barrier height, due to the Pool-Frenkel effect or phonon-assisted tunneling [9, 15].

4. Conclusions

DLTS analysis confirmed there was one, dominant, deep-level defect present in all the tested, commercially available SiC Schottky barrier diodes. The obtained activation energy and the capture cross sections of the deep trap, labelled T1, were 0.29-0.3 eV and 4-8 $\times$ 10^{-15} cm^2, respectively. Capture kinetics measurements for the related trap revealed there is a continual increase in the amplitude of the DLTS-peak as the filling pulse time increased. This feature is characteristic either of dislocation-related defects or of metastable defects. At this point of study, it is difficult to distinguish between the two. The important thing is that the electrical activity of the T1 trap, as revealed by DLTS, is most probably responsible for the observed discrepancies in the electrical characteristics of the tested diodes.

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