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DLTS Analysis of Deep Levels in 4H-SiC Schottky Barrier Diode under Different Measurement Parameters

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Abstract. This paper investigates the effect of DLTS measurement parameters on characterizing deep level defects in 4H-SiC Schottky barrier diode (SBD). By adjusting parameters such as the time window (t_W), pulse time (t_P), reverse voltage (U_R), and pulse voltage (U_P), the underlying mechanisms influencing defect peak positions, signal amplitudes, and peak broadening are analyzed. Experimental results reveal three deep level defects identified in 4H-SiC SBD: majority carrier traps T1 (E_C - 0.66 eV) and T2 (E_C - 1.0 eV), along with minority carrier trap T3 (E_V + 1.1 eV). Parameter settings not only influence defect characterization sensitivity and concentration calculations but also reveal the dynamics of carrier capture and emission. Through the thorough analysis of the DLTS signal and behavior under different DLTS measurement conditions, the electronic properties and concentration profiles of deep level defects in 4H-SiC epitaxial layers are determined.

Introduction

4H-Silicon carbide (4H-SiC) is one of the remarkable wide bandgap semiconductor materials due to its extraordinary properties, such as high breakdown electric field, high electron saturation drift velocity, and high thermal conductivity. Consequently, it is extensively utilized in high-power, high-temperature, and high-voltage applications [1, 2]. However, deep level defects are key factors affecting the performance of 4H-SiC devices, significantly reducing carrier lifetime, mobility, and device reliability [3].

Deep level transient spectroscopy (DLTS) is a powerful technique widely used for studying deep level defects in semiconductors [4, 5]. It can determine critical defect parameters, such as energy level position in the bandgap, capture cross-section, and defect concentration (N_T). Still, the accuracy and resolution of DLTS measurements highly depend on the settings of the measurement parameters. This paper aims to systematically analyze the effects of key DLTS measurement parameters on the characterization results of deep level defects of 4H-SiC, including the time window (t_W), pulse time (t_P), reverse voltage (U_R), and pulse voltage (U_P). The findings aim to provide a crucial experimental and theoretical basis for the precise analysis of deep level defects in 4H-SiC with DLTS measurements.

Experimental

The sample used in this study is 4H-SiC Schottky barrier diode (SBD), with its structural schematic shown in Fig. 1(a). The device, fabricated by Guangzhou Summit Power Semiconductor Co., Ltd., has an active area of 3.24 mm². The current-voltage (I-V) characteristics of the device demonstrated good rectification, with an ideality factor of 1.05 and a Schottky barrier height of 1.2 eV. Furthermore, capacitance-voltage (C-V) curve analysis indicates a doping concentration of 8.6×10^{15} cm^{-3} for the n-type epitaxial layer, as shown in Fig. 1(b).

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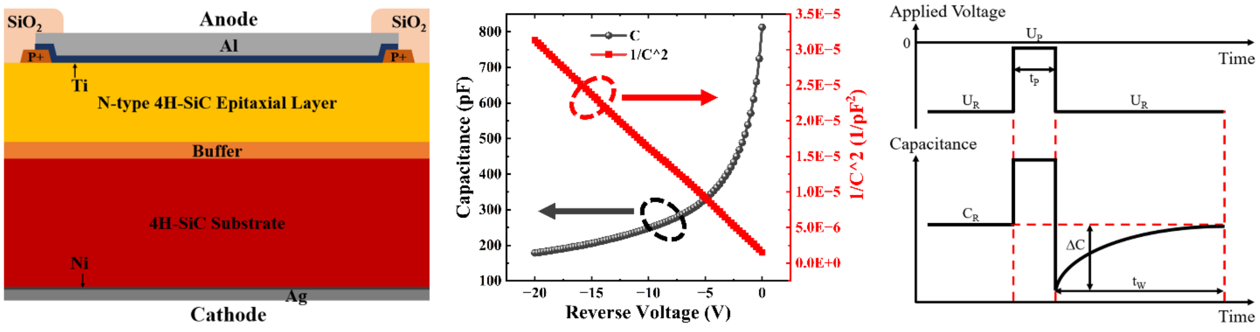
DLTS measurements are conducted over the temperature range from 100 K to 700 K using a PhysTech FT-1230 HERA-DLTS. DLTS spectra are acquired under various conditions by adjusting measurement parameters, including t_W, t_P, U_R, and U_P. A typical diagram of the DLTS measurement parameters and resulting transient capacitance is shown in Fig. 1(b). The measurement procedure is as follows: the sample is initially maintained under U_R. The U_P is then applied to fill the traps in the space charge region with carriers. At the end of U_P, the bias voltage reverts to U_R, initiating the carrier emission process. The subsequent capacitance transient is recorded over a specified t_W. The influence of these DLTS parameters on the derived defect characteristics in SiC is systematically analyzed.



(a) (b) (c)

Fig. 1. (a) Schematic diagram of 4H-SiC SBD structure. (b) C-V characteristic of 4H-SiC SBD. (c) Diagram of the DLTS measurement parameters and transient capacitance signals generated during carrier emission.

Result and Discussion

Effect of Time Window on DLTS Spectra

In DLTS signals, peaks can be observed when the trap emission rates (e_T) match the t_W. Changing t_W results in peak positions to shift with temperature, allowing the e_T to be measured through temperature scanning. As shown in Fig. 2(a), all peaks shift towards lower temperatures with increasing t_W. This shift occurs because a longer t_W corresponds to a slower e_T. Since the e_T of a trap follows an exponential dependence on the inverse temperature, a slower e_T is matched at a lower temperature [4].

$$e_T = N_{c,v}\sigma v_{th} exp\left(-\frac{\Delta E}{k_B T}\right) \tag{1}$$

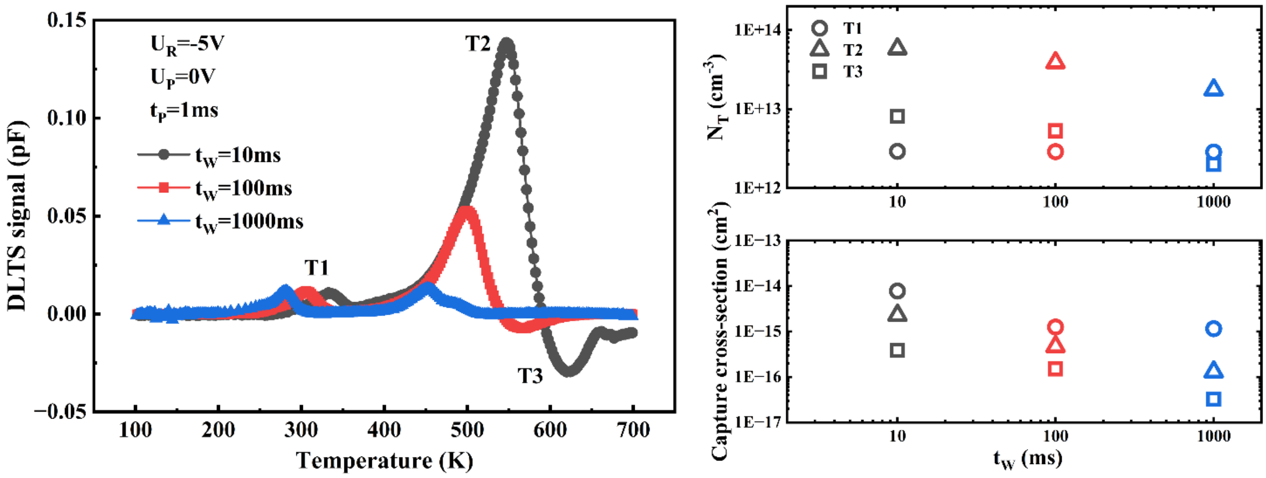
Where σ is the trap capture cross-section, v_{th} is the thermal velocity of carriers, ΔE is the activation energy of the trap, and $N_{c,v}$ is the effective density of states in the conduction band or valence band.

Fig. 2(a) shows the DLTS spectra of 4H-SiC SBD measured under different t_W. Three signal peaks are observed: a positive peak appearing in the temperature range from 280 K to 330 K, labeled T1; a positive peak appearing in the range from 450 K to 550 K, labeled T2; and a negative peak appearing in the range from 570 K to 620 K, labeled T3. As t_W increases, the amplitude of T1 peak remains essentially unchanged, while the amplitudes of T2 and T3 peaks decrease obviously. The peak amplitude of the DLTS signal is proportional to the N_T. Fig. 2(b) shows defect information derived from Arrhenius plot fitting under different t_W, including σ and N_T. As t_W increases, the N_T of T2 and T3 decreases. Shorter t_W is more sensitive to defects with faster e_T, whereas a longer t_W primarily detects defects with slower e_T. Consequently, if t_W does not match the e_T of defects contributing to T2 and T3 peaks, the signal amplitudes of the peaks decrease.

The deep level trap T1 is identified as a majority carrier trap with the energy level located 0.66 eV below the bottom of the conduction band (E_C). It exhibits a symmetric Gaussian-shaped peak and a single-exponential emission kinetics and these are characteristics of point defects. The measured ΔE and σ of T1 are consistent with the fingerprint of the $Z_1/_2$ center, an intrinsic defect complex in n-type 4H-SiC. The $Z_1/_2$ center, which is commonly attributed to a carbon vacancy (V_C) or related complex, can act as a lifetime-killing recombination center and is commonly observed in DLTS spectra of as-grown 4H-SiC epitaxial layers [6].

T2 is a majority carrier trap with the activation energy of at E_C - 1.0 eV. It exhibits broad and asymmetric DLTS peaks, which suggests T2 is not related to the discrete point defects. T2 may correspond to envelope peaks formed by multiple defects with close energy levels or the extended defect [7, 8].

T3 is a minority carrier trap with the energy level located 1.1 eV below the valence band top (E_V + 1.1 eV). The 4H-SiC SBD is a unipolar device where minority carriers are typically absent under reverse bias. However, the presence of the P+ region can serve as a source of minority carrier injection under specific measurement conditions. This injection makes the detection of the minority carrier traps such as T3 possible [9, 10]. T3 exhibits a broad and asymmetric DLTS peak, which is characteristic of interface states at the metal/SiC interface or extended defects rather than point defects. Extended defects in 4H-SiC, such as stacking faults, dislocation clusters, or basal plane dislocations, can introduce broad distribution of energy levels within the bandgap due to strain fields and localized electronic states. These defects act as minority carrier trapping centers and can significantly affect carrier recombination and device reliability.



(a) (b)

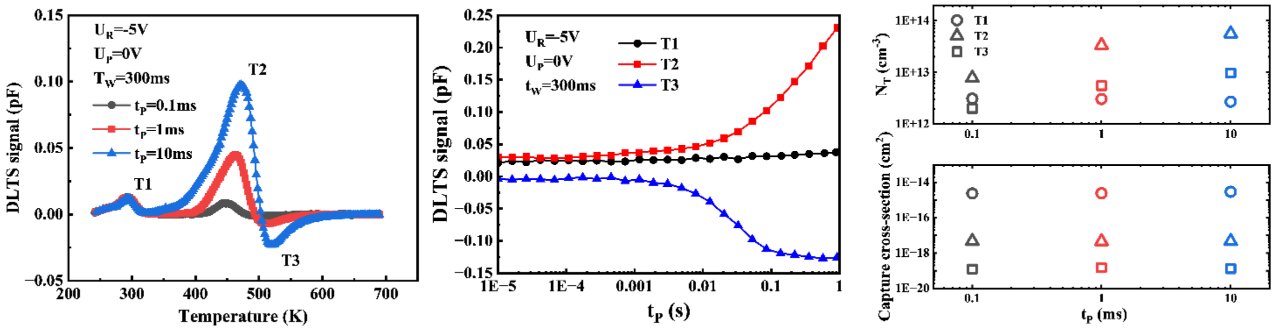
Fig. 2. (a) DLTS spectra and (b) defect information of 4H-SiC SBD under different t_W.

Effect of Pulse Time on DLTS Spectra

Fig. 3(a) illustrates the effect of t_P on the DLTS spectrum. As t_P increases, the position and shape of T1 peaks remain unchanged, indicating that its trap filling saturates rapidly even at the shortest t_P. This result is consistent with the data in Fig. 3(b) that the amplitude of T1 peak does not exhibit significant variation with t_P, which is characteristic of the capture kinetics of a point defect. In contrast, as t_P increases, the T2 and T3 peaks shift to higher temperatures, gradually broaden, and their amplitude continues to increase over the entire test range in agreement with the trend in Fig. 3(b). This behavior strongly suggests the presence of a more complex capture mechanism involving defects with a continuous energy distribution. This feature of T2 peak is typically regarded as the fingerprint characteristic of spatially extended defects such as dislocations, stacking faults, or defect clusters [11, 12]. The capture process in such defects is governed by a combination of factors. These include potential barriers around the defect core, carrier re-emission during capture, or a distribution of capture rates. These factors lead to the observed slow, non-exponential filling behavior. As a minority carrier trap, T3 exhibits amplitude saturation when t_P exceeds 100 ms. However, it also demonstrates significant increase before saturation, suggesting it possesses non-point defect kinetic properties. These characteristics are associated with defect clusters or interface states at the metal/SiO_2 interface.

The defect parameters extracted from Arrhenius plots under different t_P are summarized in Fig. 3(c). As t_P increases, the σ of all three defects shows no obvious change. For N_T, along with the increase of t_P, the values for T2 and T3 exhibit an upward trend, while T1 remains almost unchanged.

Therefore, the t_P used in this work can reveal the kinetic characteristics of T2 and T3 and confirm their non-point defect nature. It should be noted that accurate quantification of the total concentration of extended defects like T2 and T3 requires measurements at longer t_P to ensure complete trap filling.

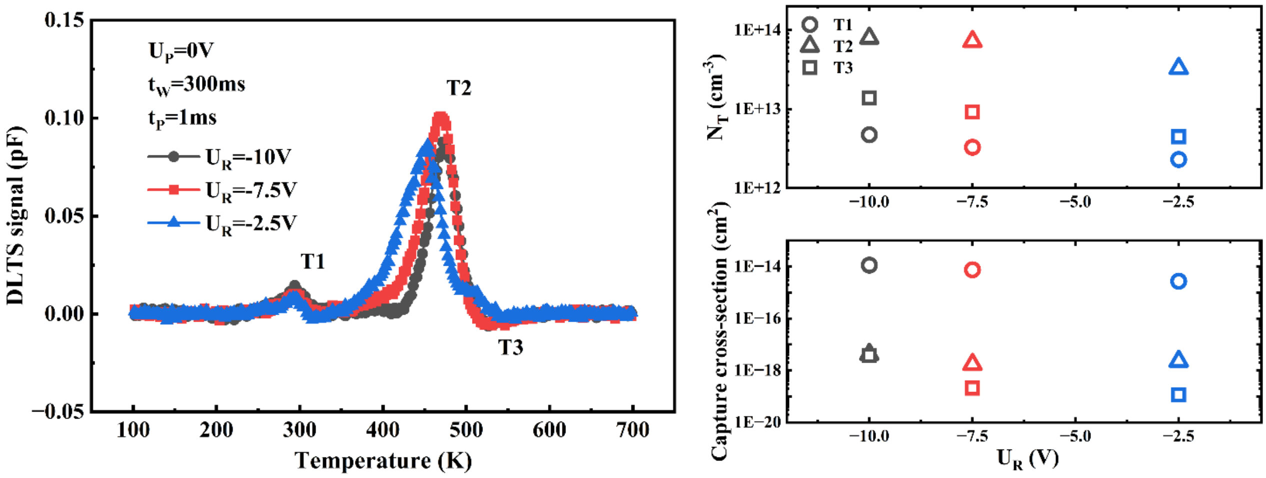


(a) (b) (c)

Fig. 3. (a) DLTS spectra of 4H-SiC SBD under different t_P, (b) amplitudes of DLTS peaks as a function of the logarithm of the t_P, and (c) defect information extracted from Arrhenius analyses.

Effect of Reverse Voltage on DLTS Spectra

Fig. 4 shows the DLTS spectra and the corresponding defect information under different U_R. As the absolute value of U_R decreases ($|U_R|$), the N_T of three defects reduces due to the narrowing of the detection depletion region width. The depth of the depletion region width can be tuned by applying different U_R values and in this way defect profile information can be obtained. The signal amplitudes of T2 and T3 peaks exhibit non-monotonic and irregular fluctuations with changing U_R. This behavior indicates an uneven distribution of these defects, further corroborating their association with extended defects. Such distribution characteristics are typically observed in defect clusters or extended structural defects.

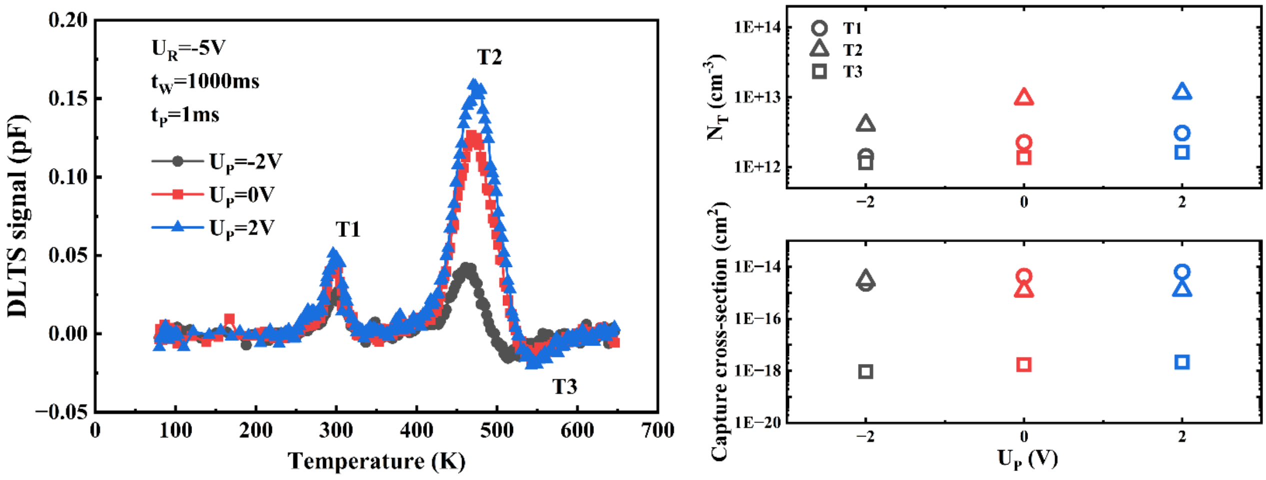


(a) **(b)**

Fig. 4. (a) DLTS spectra and (b) defect information of 4H-SiC SBD under different U_R.

Effect of Pulse Voltage on DLTS Spectra

Fig. 5 shows the DLTS spectra and the derived defect information under different U_P. As U_P increases, the depletion region width of the diode becomes narrower during U_P period. This reduction allows more carriers to inject into the detection region, thereby filling more deep level traps, resulting in an enhanced DLTS signal. For varied U_P, traps located at different depth scan be filled due to the corresponding changes in band bending. This capability enables the analysis of the spatial distribution of defects along with the depth. When utilized in combination with U_R, U_P can be effectively employed to distinguish between the deep level defects in bulk material and the interface states [13].



(a) (b)

Fig. 5. (a) DLTS spectra and (b) defect information of 4H-SiC SBD under different U_P.

Summary

In conclusion, this study employs DLTS to measure three deep-level centers in 4H-SiC SBDs. The effects of different measurement conditions on the deep-level defects at different energy levels are compared. The result indicates that t_W corresponds to the emission rate of specific traps; it can be used to distinguish between point defects and the extended defects. As t_P increases, the amplitude of deep level trap peaks gradually saturates. Therefore, a higher t_P is recommended for more precise detection of defects at specific energy levels. Furthermore, by precisely controlling the U_R and U_P, the concentrations and depth distributions of defects in the epitaxial layer can be quantitatively determined, enabling the distinction between the bulk traps and the interface traps. This paper offers crucial experimental evidence and theoretical basis for the precise characterization of deep level defects and the optimization of DLTS measurement protocols.

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