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Investigation of the distribution of deep levels in 4H-SiC epitaxial wafer by DLTS with the method of decussate sampling

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ABSTRACT

In this paper, Schottky structures were fabricated on the epitaxial wafers and the deep levels of the wafers were measured by deep level transient spectroscopy (DLTS). The thickness of the commercial n-type 4°off-axis 4H-SiC (0 0 0 1) epitaxial wafers was 100 µm, with a doping concentration of 2×10^{14} cm^{-3}. Nine sample points were selected along with the direction of [1–100] and [11–20] on the wafer. Through the peak fitting analysis of the test results, the detailed information of deep level defects in the epitaxial layer was obtained. The typical deep level defect $Z_{1/2}$ was found, but Ti center did not appear, which indicates that Ti center was not introduced in our technological process. Defect concentration uniformity of the 4-inch 4H-SiC epitaxial wafer is 5.74%. The results demonstrate that although the concentration of $Z_{1/2}$ defect differs in different locations, but the difference is so small that $Z_{1/2}$ defect concentration can be considered to be evenly distributed across the wafer.

1. Introduction

Silicon carbide (SiC) is a promising material in the field of high voltage applications due to its excellent material properties, which are wide bandgap, high critical electric field, radiation resistance, high saturation velocity, and high thermal conductivity [1–3]. Significant progress has been made in the research of 4H-SiC materials and devices in recent years, and those research outputs speed up the practical application of silicon carbide. However, there are still many problems need to be solved to promote silicon carbide widely used in practical application scenario. One of the problems is related to intrinsic deep level defects like $Z_{1/2}$, which is mainly caused by carbon vacancy and silicon vacancy [4]. Intrinsic deep level defects usually act as traps or composite centers in wafers, and they will reduce the carrier lifetime and affect the bipolar 4H-SiC device performance [5]. Therefore, the investigation on the deep level defects is one of the main research fields of silicon carbide.

In recent years, scientists mainly focus their researches on the types of deep levels in the as-grown 4H-SiC epilayers. Meanwhile, they develop methods to control the types and concentrations of deep levels through irradiation or C^+-implantation/annealing process, so as to achieve the purpose of controlling carrier lifetime in the wafer [6–10]. However, it is relatively rare to study deep level defects from the perspective of the whole wafer. Studying the distribution of intrinsic deep levels on the whole wafer is useful to understand the formation of intrinsic deep levels and improve device yield. In this work, we first measured the defect information across the 4H-SiC epilayer through deep level transient spectroscopy (DLTS), by sampling evenly over the whole wafer, and fabricating Schottky structures. The deep level defect signals are tested by DLTS through the transient changes in space charge areas. The Schottky structures are fabricated on the surface of epitaxial layer, so Schottky space charge areas expand inward on the surface of epitaxial layer. At last, we analyzed and summarized the distribution of defects on the wafer. The distribution of deep level defects in the epitaxial layer of 4-inch n-type 4H-SiC is investigated, and it can not only avoid the possible influence of sampling locations at different positions in subsequent experiments, but also feedback the epitaxial growth stage to reduce the deep level defects.

2. Experimental

In order to identify the types of deep levels and investigate the distribution of traps in the wafer, n-type 4H-SiC epitaxial layer was grown on the Si-face of a commercial 4°off-axis 4H-SiC wafer. The

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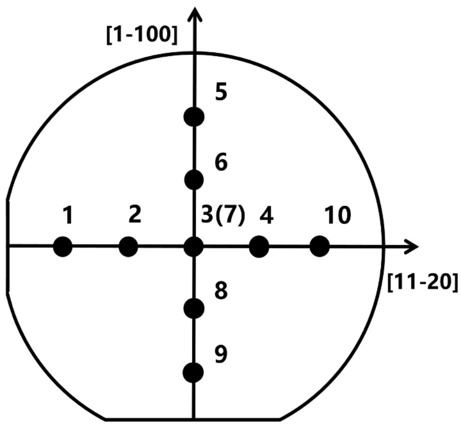

Fig. 1. The locations of nine sample points on the wafer.

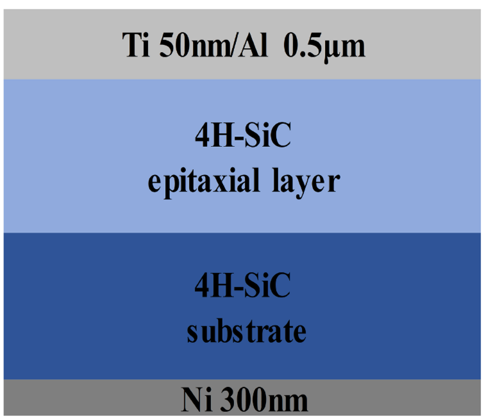

Fig. 2. Schematic diagram of Schottky structure of the samples.

thickness of the epitaxial layer is 100 μm, with a net donor concentration of 2×10^{14} cm^{-3}. Nine sample points are sampled along with the directions of [1–100] and [11–20] to fabricate Schottky structures, which can be measured and analyzed by DLTS with the mode of deep level transient Fourier spectroscopy (DLTFS). The positions of nine sample points in the wafer are shown in Fig. 1, and dies with an area of 15 mm × 15 mm at each sample position were obtained by laser cutting. Nine samples were cleaned by RCA process, with a BOE bath to remove the natural oxide layers on the both sides. Next, a 300-nm Ni layer was sputtered on the C-face of each sample and annealed by rapid thermal annealing (RTA) in N_2-ambient at a temperature of 1000 °C for 90 s to create Ohmic contacts. Finally, a metal stack of Ti (50 nm)/Al (500 nm) was e-beam evaporated on Si-face of each sample using a shallow mask to form Schottky contacts. The sample structure is shown in Fig. 2.

3. Results and discussion

DLTS measurement was performed on the nine Schottky structures by the mode of DLTFS. The test parameters of the samples such as reverse bias voltage (U_R), pulse voltage (U_P), period width (T_W) and pulse width (t_P) are given in the legends, and better signal spectra are obtained under these parameter settings. The defect information of deep levels is calculated from Arrhenius plots, which are drawn by the Arrhenius Eq. (1),

$$\ln(\tau_e v_{th} N_C) = \frac{E_C - E_T}{k}\frac{1}{T} - \ln(X_n \sigma_n) \quad (1)$$

Here, τ_e is the emission time constant, v_{th} is the electronic thermal velocity, N_C is the effective density of states, E_C is the edge of conduction band, E_T is the defect level in the bandgap, k is the Boltzmann constant, T is the temperature, X_n is Entropy factor for electrons and σ_n is capture cross section for electrons [11].Therefore, the defect energy is obtained from the slope and the capture cross section from the intercept of the Arrhenius curves.

DLTS measurement and fitting results of all the Schottky structures are shown in Fig. 3. Locations of Sample-1~sample-10 on the wafer correspond to the numeric labels in Fig. 1. Nine Schottky structures were measured by DLTS in the temperature range from 80 K to 500 K, which includes the temperature range of Ti and $Z_{1/2}$ deep levels' DLTS signals [12]. As shown in Fig. 3, there is no Ti center signal in the measure results of nine Schottky structures. This means that Ti impurity are not introduced into the SiC side of the Schottky contact interface although Ti center is one of the deep levels that typically occur in n-Type 4H-SiC, and the cause of Ti center is Ti, Cr or other metal impurities. The test result indicates that Al/Ti contact process we adopted in this work is feasible. In addition, deep level signal peaks are found near 300 K of all the Schottky structures, and the Arrhenius plots are obtained by fitting the signal peaks. The deep level signals obtained from nine Schottky structures are related to typical $Z_{1/2}$, whose energy level locates in ~0.67 eV below the conduction band edge [13]. Although the formation mechanism of $Z_{1/2}$ defect is still unclear, it is generally believed that it is related to carbon vacancy [14].

As shown in Table 1, defect energy and capture cross section of the nine samples are calculated from Arrhenius plots. Meanwhile, defect concentration is obtained from DLTS signal b1 and the area of Schottky barrier electrode.

The positions of deep levels in Table 1 are not completely consistent, which are caused by errors in the testing process and the fitting analysis process. Within the margin of error, it can be judged that the signal peaks of the nine samples caused by the same defect, and the deep level positions of the defect are almost the same as that of $Z_{1/2}$ defect. Capture cross section is a symbol of the capture carrier probability of the composite center, which will have a direct influence on carrier lifetime. The distribution of $Z_{1/2}$ defects concentration in the direction of [1–100] and [11–20] on the wafer is shown in Fig. 4, from which we found that $Z_{1/2}$ is almost uniformly distributed in 4H-SiC as-grown epitaxial wafers, because the concentrations of $Z_{1/2}$ at different locations in the wafer are of the same order of magnitude. Obviously, the effective doping concentration at different positions of the epilayer is almost completely consistent shown as Fig. 5, so the influence of doping is exactly the same at different positions, which will not affect the analysis of defect concentration distribution. More important is that the defect concentration distribution with uniformity σ/Mean = 5.74% which is calculated by Eq. (2).

$$\sigma/M = \sum_{i=1}^{N}\left(t_i - \left(\sum_{i=1}^{N} t_i\right)/N\right)^2 / \sum_{i=1}^{N} t_i \times 100\% \quad (2)$$

The defects concentrations in the Table 1 were substituted into uniformity equation to obtain the calculated value [15], and the value indicates that defect concentration is evenly distributed over the wafer.

4. Summary

In this study, Ti center did not appear at the test temperature range from 80 K to 500 K, which shows that Al/Ti contact process we adopted in this work is advisable. Typical $Z_{1/2}$ deep level defect was found widely existing throughout 4H-SiC as-grown epitaxial wafer. Although the concentration of $Z_{1/2}$ at different locations in the wafer is not exactly the identical value, the concentrations are of the same order of magnitude. Especially, defect concentration uniformity of the wafer is 5.74%, which can be considered as uniform distribution of $Z_{1/2}$ in the wafer. Reducing or eliminating the concentration of $Z_{1/2}$ defects will effectively improve the quality of 4H-SiC wafers.

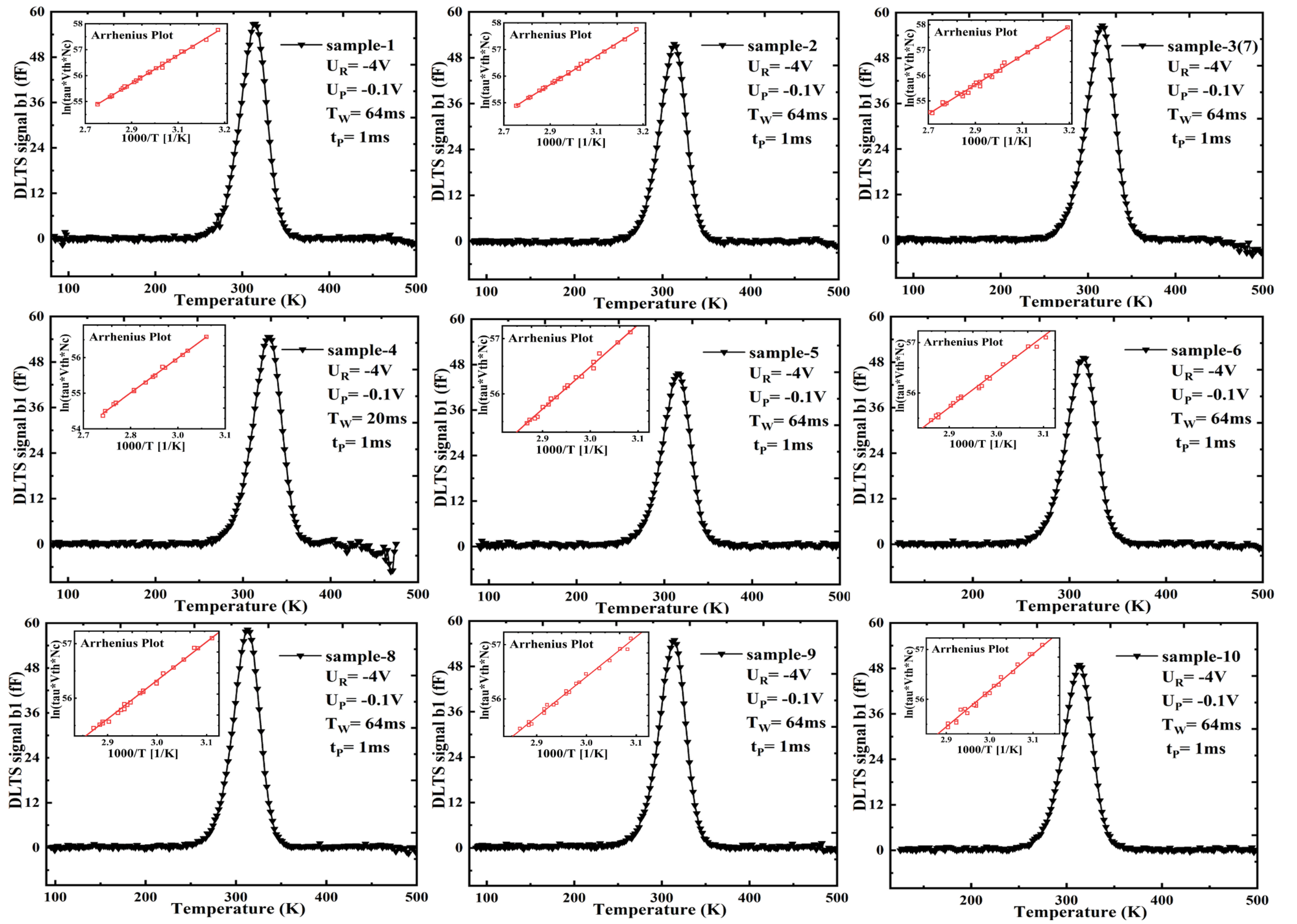

Fig. 3. DLTS signal spectrums of nine samples at the temperature range from 80 K to 500 K. Sample-1 ~ sample-10 corresponds to the nine sample points in Fig. 1. Inset: Arrhenius Plots are obtained from the fitted curves.

Table 1
The deep level information of nine Schottky structures.

	sample-1	sample-2	sample-3(7)	sample-4	sample-5	sample-6	sample-8	sample-9	sample-10
Energy (eV)	0.673	0.662	0.607	0.667	0.658	0.660	0.666	0.689	0.630
Sigma (cm^2)	4.60E-15	3.24E-15	4.17E-16	3.91E-15	2.27E-15	2.93E-15	4.03E-15	8.16E-15	1.29E-15
Nt (cm^{-3})	3.59E + 12	2.90E + 12	3.07E + 12	3.15E + 12	2.80E + 12	2.82E + 12	3.37E + 12	3.28E + 12	2.82E + 12

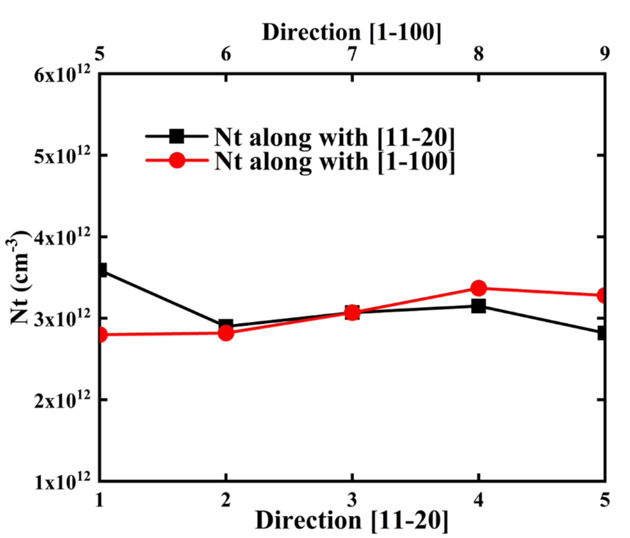

Fig. 4. The concentrations of $Z_{1/2}$ defects distribute in the direction of [11–20] and [1–100].

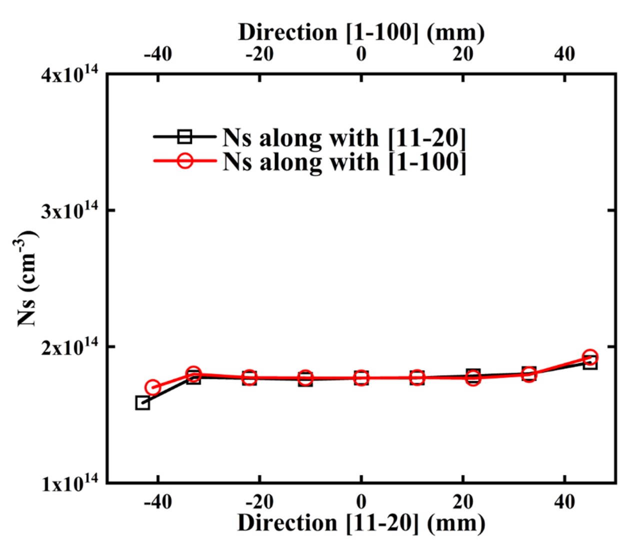

Fig. 5. The effective doping concentration of the epitaxial layer in the direction of [11–20] and [1–100].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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