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The negative temperature coefficient of the breakdown voltage of SiC p-n structures and deep centers in SiC

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Abstract. In this paper negative temperature coefficient of the 6H-SiC diode breakdown voltage is considered. It is shown that the temperature dependence of the breakdown voltage value can be explained in terms of recharging of deep centers in the space charge region of the diode. Experiments made with boron doped 6H-SiC diodes are in good agreement with calculation.

1. Introduction

In Ref. 1 it was found that in SiC p-n structures in which the electric field is applied parallel to the crystallographic axis *c* the breakdown voltage shows a negative temperature coefficient (BVTC). In a number of studies [2,3] this fact was related to the crystal structure of hexagonal SiC polytypes and to the occurrence of a natural superlattice. In some studies [4], alongside with the negative BVTC, a positive BVTC was observed and it was suggested that the negative value of BVTC might be related to recharging of deep centers, as in the case of silicon-based p-n structures [5].

2. Samples

The present study was concerned with SiC p-n structures prepared by sublimation epitaxy, with boron diffusion carried out prior to forming mesas. The electrical field in diode the p-n junction of the diode was parallel to the *c*-axis of the crystal. The structures had a negative BVTC of about $2 \times 10^{-3} \text{ K}^{-1}$. The absolute value of BVTC depended on temperature and dropped by about an order of magnitude when the junctions were heated to 600K.

3. Theory and experiment

To find an explanation for the observed negative values of BVTC we considered, following the authors of refs. 4 and 5, the effect of recharging of deep centers. It is known that boron in SiC introduces two types of deep acceptor levels, the deeper level (D-center) having the following parameters:

$$E_V + 0.58 \text{ eV}, \sigma_p = 1 - 3 \times 10^{-16} \text{ cm}^2, \sigma_n = 1 - 3 \times 10^{-20} \text{ cm}^2$$

The model we suggested is based on the recharging of deep acceptor levels in a lightly doped p-type intermediate layer near the metallurgical boundary of the p-n junction.

We made two assumptions:

- (i) The region of avalanche multiplication is situated in the low doped p-type region near the metallurgical boundary of the p-n junction.
- (ii) The concentration of deep acceptor centers is comparable to that of shallow acceptors.

Such a region can be formed through overcompensation of the n-type region during the diffusion of acceptor impurities (boron, for example). The presence of a region of this kind in our samples has been shown experimentally [6]. The breakdown voltage of a p-n junction is given by the well-known equation:

$$U_{br} = \frac{\epsilon_a E_{cr}^2}{2qN_i} \quad (1)$$

where ϵ_a is the statistic permittivity, E_{cr} is the critical electric field, q is the electron charge, N_i is the impurity concentration in the base region.

Taking into account deep acceptor levels in the low doped p-base, we can write :

$$U_{br} = \frac{\epsilon_a E_{cr}^2}{2q(N_S + KM)} = \frac{U_{bro}}{(1 + KM/N_S)} \quad (2)$$

where N_S is the concentration of shallow acceptor impurities, K is the electron occupancy of the deep acceptor level, and $K = (M-m)/M$, where M is the total concentration of deep levels; m is the concentration of deep acceptors occupied by the holes, U_{bro} is the breakdown voltage of p-n junction without deep acceptors.

When $U \ll U_{br}$, there is practically no current through the p-n junction and all deep acceptors in the p-type layer are occupied by electrons ($K=1$). When $U \sim U_{br}$, avalanche multiplication occurs in the space charge region and holes are captured by deep acceptors. Because acceptors occupied by holes are neutral, K decreases and, consequently, the electrical field becomes weak. This leads to an increase in the observed value of the U_{br} . It should be noted that the level occupancy depends on temperature and decreases with heating. For this reason, U_{br} will decrease with temperature, so we can see negative BVTC.

Based on the Shockley-Read statistics we can write the following equation for the discharging rate of deep acceptors in our case :

$$\frac{dm}{dt} = (M - m)\Delta p \alpha_p - m \alpha_n \Delta n - \alpha_p \beta_i m \quad (3)$$

Here, $\Delta p = \Delta n$ is the carriers concentration; $\alpha_n(p) = \sigma_n(p)V_t$, where $\sigma_n(p)$ is the electron (hole) capture cross section of the deep acceptor, V_t is the thermal velocity; and $\beta_i = N_V e^{-\frac{E_i}{kT}}$, where N_V is the density of state in the valence band, E_i is the ionisation energy of the deep acceptor, T is the absolute temperature; k is the Boltzmann constant.

For the case of constant current ($dm/dt = 0$), and taking into account that $\alpha_p \gg \alpha_n$, we obtain from (3) the following equation for K :

$$K = \beta_i (\Delta p + \beta_i)^{-1} \quad (4)$$

Equations (4) and (2) give for U_{br} :

$$U_{br} = U_{bro} \frac{1 + M\beta_i}{N_S(\Delta p + \beta_i)} \quad (5)$$

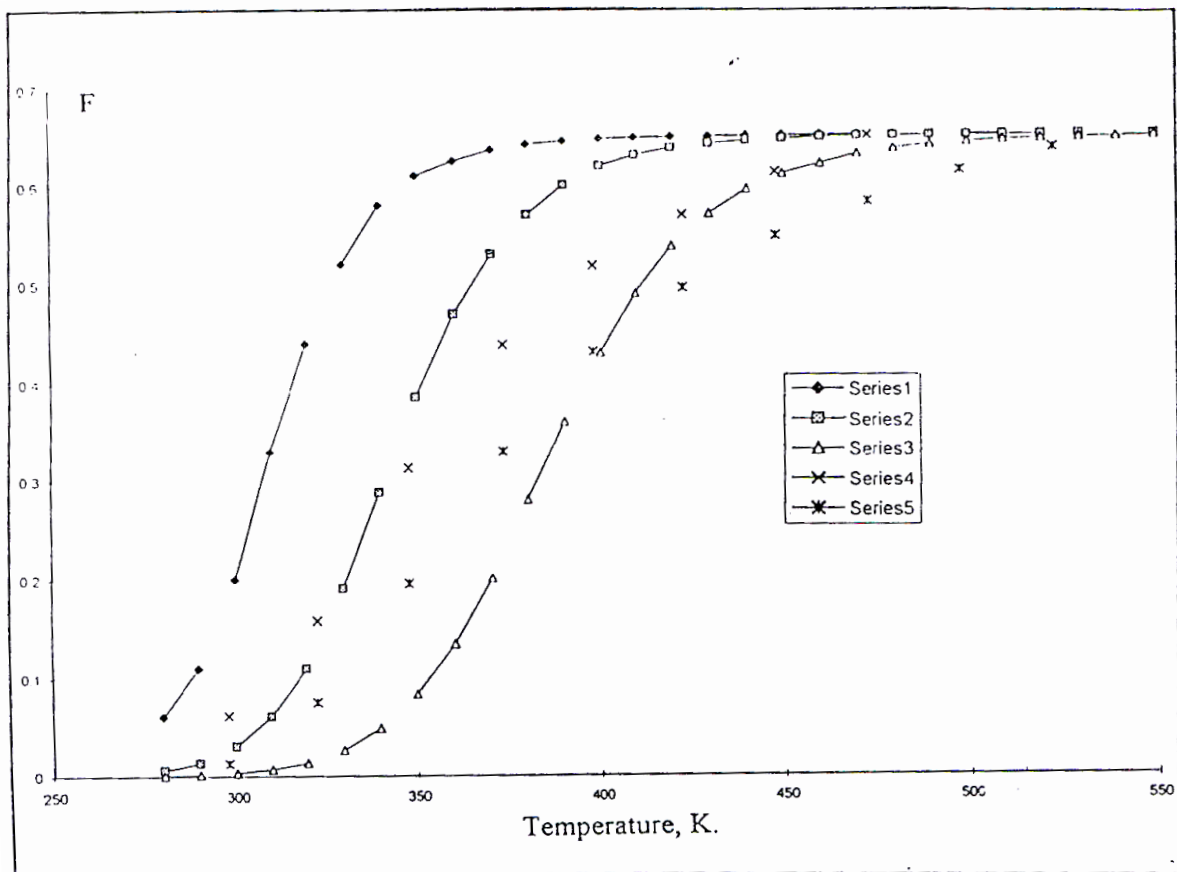


Figure 1: temperature dependence of calculated (1-3) and experimental (4-5) values of F . Calculations were made for the following Δp values, cm^{-3} : $1 \cdot 10^{10}$; $2 \cdot 10^{11}$; $3 \cdot 10^{12}$. The experimental values of U_{br} correspond to breakdown currents: 4-100 mA; 5-500 mA.

Fig. 1 shows experimental and calculated values of $F = U_{br}/U_{bro}-1$. The following parameters were used in calculation: $U_{bro} = 800$ V, $M/N_S = 0.65$ and $NV = 5.10^{15} \times T^{3/2} \text{ cm}^{-3}$. As one can see in the figure the best agreement between experimental and theoretical results is obtained for Δp of about $10^{11}-10^{12} \text{ cm}^{-3}$. However the magnitude of Δp calculated from the value of the breakdown current as $\Delta p = J/V_{sq}$ (where J is the current density in the p-n junction and V_S is the drift velocity) is $10^{10}-10^{11} \text{ cm}^{-3}$. This discrepancy can be explained, from our point of view, if we take into account the fact that the breakdown in SiC usually takes place in small areas (microplasma breakdown) whose size is several orders of magnitude less than the total area of the p-n junctions. But when we calculate the current density we take the total area of the p-n junction. In other words, actual current density (and the Δp value) may be higher by one order of magnitude in the breakdown areas which coincides with the value needed by the theory.

4. Summary

The temperature dependence of BVTC calculated in terms of our model and known D-denter parameters shows a good agreement with experiments. Because the boron diffusion is widely used for protecting the periphery of SiC mesas from surface breakdown [1,6] and because boron (D-center) is a typical background impurity in SiC fabricated by various techniques [7], the problem of the BVTC sign can be, in our opinion, ultimately solved only by taking into account (or eliminating) the effect of D-centers in studies of breakdown voltage in SiC p-n structures.

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