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Analytical models of on-resistance and breakdown voltage for 4H-SiC floating junction Schottky barrier diodes ☆

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ABSTRACT

The analytical models of on-resistance and reverse breakdown voltage for 4H-SiC floating junction SBD are presented with the analysis of the transport path of the carriers and electric field distribution in the drift region. The calculation results from the analytical models well agree with the simulation results. The effects of the key structure parameters on specific on-resistance and breakdown voltage are described respectively by analytical models. Moreover, the relationship between BFOM and parameters of floating junction are investigated. It is proved that the analytical models are more convenient for the design of the floating junction SBDs.

1. Introduction

SiC has more advantages over Si material, such as large band gap, high critical breakdown electrical field strength, high electron saturation velocity and excellent bonding characteristics stability. Compared with Si Schottky barrier diode (SBD), SiC SBD shows a great potential in power applications because of lower leakage current and faster switching speed [1]. However, there is also a tradeoff between breakdown voltage (BV) and specific on-resistance (R_{on}). To solve this issue, SiC floating junction SBD (FJ_SBD) is put forward [2,3]. Floating junction changes the electric field distribution in the drift region, greatly improving the breakdown voltage at the same specific on-resistance. However, inappropriate design of the floating junction structure also reduces the performance of the device, even lower than that of conventional SBD. In order to optimize the device design, simulation tools such as ISE-TCAD or MEDICE and analytical model are usually used. Comparing with simulation tools, analytical model is more explicit and efficient, which can continuously obtain the relationship between device structure parameters and guide to select the appropriate device structure. Therefore, it is important to propose an analytical model for designing the device and optimizing the power of merit. At present, some analytical models for conventional SBDs have been presented [4–7], but for a FJ_SBD, researches were mainly based on numerical simulations [8].

In this paper, the analytical models of specific on-resistance R_{on} and reverse breakdown voltage BV for 4H-SiC FJ_SBD are proposed to analyze the effect of main parameters of floating junction on the specific on-resistance and breakdown voltage, and to optimize the structure of device effectively.

2. The model of specific on-resistance

The schematic cross section of the 4H-SiC FJ_SBD cell is shown in Fig. 1. Difference comparing with conventional SBD is only a series of P^+ islands inserted in the N^- epitaxial layer of SBD, named floating junction, which can be formed by ion implantation plus multiple epitaxial technique. Basically, FJ_SBD consists of many cells as same as the structure shown in Fig. 1 and the distributions of current density and electrical field are same each other, according to simulation with ISE simulator.

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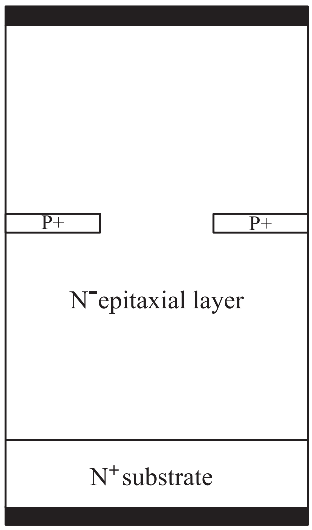

Fig. 1. Schematic cross section of the 4H-SiC FJ_SBD.

Meanwhile, when the back ohmic contact area is much larger than the Schottky contact area, the spreading resistance, namely the two-dimensional character, should be considered. But based on the literature [9], the spreading resistance could be ignored when the epitaxial layer thickness is much smaller than the radius of the Schottky contact, which is satisfied in general for the reality fabricated SiC power device. In addition, the spreading resistance effect is not nearly existence for SiC power discrete devices, in which the back ohmic contact area is only slightly larger than the Schottky area. According to the discussion above, the whole on-resistance of a SiC FJ_SBD could be regarded as contributed by epitaxial resistance.

In a FJ_SBD, the basic forward conduction mechanism is similar as that of a conventional SBD. Meanwhile, the space between floating junctions should not be pinched off at zero and forward bias condition, which guarantees that the forward current could pass through the space of the P^+ floating junctions. As shown in Fig. 2, different from the conventional SBD, the current flow is crowded when electron passing through the space. So the total resistance of a FJ_SBD is contributed by a series of resistances of the conduction paths through the space of floating junctions with the current spreading above and below the floating junctions. A floating junction unit cell with stripe geometry is shown in Fig. 3. In this FJ_SBD structure model, W is the width of a junction and S is the space width between the two floating junctions. Depletion width of a floating junction is W_j. t_{epi}, t_{epi2} and t_3 are the total thickness of the epitaxial layer, the regrown epilayer thickness and the thickness of a floating junction respectively.

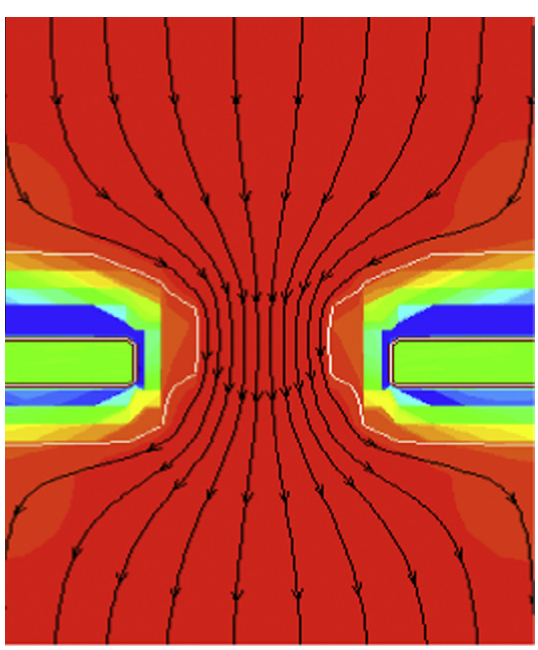

Fig. 2. Simulated current path in the FJ_SBD cell during forward conduction.

In this model, the R_{on} consists of five different components, which are channel resistance (R_3), two spreading region resistance (R_4) and two drift region resistances (R_1, R_2). t_1, t_2 and M can be respectively given by

$$M = \frac{S}{2} - W_j \tag{2.1}$$

$$x = \left(\frac{1 - \sin 45^\circ}{\sin 45^\circ}\right) W_j \tag{2.2}$$

$$t_1 = t_{epi2} - \frac{t_3}{2} - x - \left(\frac{W+S}{2} - M\right) \tag{2.3}$$

$$t_2 = t_{epi} - t_{epi2} - \frac{t_3}{2} - x - \left(\frac{W+S}{2} - M\right) \tag{2.4}$$

and then,

$$R_1 = \rho \cdot t_1 \tag{2.5}$$

$$R_2 = \rho \cdot t_2 \tag{2.6}$$

$$R_3 = \rho \cdot (t_3 + 2x) \cdot \frac{W+S}{2M} \tag{2.7}$$

$$R_4 = \frac{W+S}{2} \rho \cdot \int_0^{\left(\frac{W+S}{2} - M\right)} \frac{1}{M+y} dy \tag{2.8}$$

where ρ is the resistivity of the epitaxial layer.

$$\rho = \frac{1}{N_D q \mu} \tag{2.9}$$

$$\mu = \mu_{\min} + \frac{\mu_{\max} - \mu_{\min}}{1 + \left(\frac{N_D}{N_{ref}}\right)^{\beta}} \tag{2.10}$$

Here N_D is the doping concentration included impurity incomplete ionization, μ is the electron mobility of the epitaxial layer, $\mu_{\max} = 950\ cm^2/V\ s$, $\mu_{\min} = 40\ cm^2/V\ s$, $N_{ref} = 2 \times 10^{17}\ cm^{-3}$, and $\beta = 0.76$ [10]. So the specific on-resistance R_{on} of a FJ_SBD is determined by Eq. (2.11)

$$R_{on} = R_1 + R_2 + R_3 + 2R_4 \tag{2.11}$$

The results from analytical model presented above are verified by the results simulated by the simulator of ISE-TCAD. The R_{on} of a FJ_SBD versus the doping concentration and the width (W) of P^+ junction and its spacing (S) are shown in Fig. 4(a) and (b). The trends of simulation and analytical model results in different epilayer layer thickness and doping are in well agreement. In Fig. 4(a), the both of specific on-resistances decrease rapidly as the doping concentration increasing, as same as a conventional SBD. And Fig. 4(b) shows the R_{on} reduces with S increasing, because the wider the S, the larger the channel current. Meanwhile, the R_{on} versus different S and W is listed in Table 1, indicating R_3 and R_4 to be the main domination components. The results also prove that the width and space of the floating junction are more important