Current Mechanisms in n-SiC/p-Si Heterojunctions

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Abstract— Current-voltage characteristics of 3C-SiC/Si heterojunction diodes are presented with reverse breakdown voltage exceeding 200V, leakage current of 1.3mA/cm^2 at 200V, and a $\pm 1\text{V}$ rectification ratio of 200,000. The reverse leakage current was observed to have both temperature and field dependence and hence a model is presented to explain this observation based on a trap assisted tunneling-thermal emission mechanism located at the SiC/Si interface. With further improvements in the SiC crystal quality at the silicon interface, trap concentrations and thus reverse bias leakage currents will be reduced.

Keywords—3C-SiC; heterojunction diode; current mechanism

I. INTRODUCTION

The SiC/Si heterojunction has been investigated as a promising candidate in many semiconductor device applications, including high-voltage and high-frequency diodes [1],[2] heterojunction bipolar transistors [3],[4] and photovoltaic cells [5]. Due to the wide bandgap, high thermal conductivity, and chemical stability of SiC, it is an excellent semiconductor to be combined with silicon in a heterojunction diode device. Yet, of the many different SiC polytypes that exist, only 3C-SiC has been successfully grown on silicon substrates at temperatures below the melting point of silicon [6],[7]. Many different growth techniques and chemistries have been investigated in recent years, resulting in the reduction of crystal defects that occur due to the lattice and thermal mismatch between the epi-layer and the substrate. While thicker layers exhibit good crystal quality away from the silicon interface, this interface region remains a major source of structural and electronic defects. The valence band offset between SiC and silicon (1.7eV, [8]) forms a large barrier to hole injection and in the ideal case, the reverse saturation current should be extremely low, yet due to the high density of defects at the interface the diode characteristics are far from ideal.

In homojunctions and heterojunctions the established mechanisms of trap-assisted generation in the depletion region and band-to-band tunneling at high bias are well established [9]. Some studies find space charge region generation in SiC/Si structures as evidenced by the $I \propto V^{1/2}$ relationship [4], while others propose a mechanism of excess-tunneling to explain current-voltage characteristics of n-3C-SiC/Si heterojunctions [10]. In this paper, we focus on the current mechanism responsible for the reverse bias leakage and propose a new mechanism governed by trap assisted tunneling and thermal emission that gives rise to both temperature and field dependence of the reverse current.

II. DEVICE FABRICATION AND TESTING

3C-SiC/Si samples were supplied by QsSemi and fabricated at the Queensland Microtechnology Facility. Single crystal n-type 3C-SiC was grown to a thickness of 500nm on 25 $\Omega\text{-cm}$, p-type $\langle 100 \rangle$ silicon in a hot wall CVD furnace at 1100°C with n-type doping concentration in the range $1\text{--}5 \times 10^{16}\text{cm}^{-3}$. The SiC surface was cleaned with acetone, isopropanol, and then 1% HF before depositing aluminium and patterning into $500\mu\text{m}$ by $230\mu\text{m}$ ohmic contacts with a surrounding guard ring to reduce surface leakage currents. The back silicon surface was etched in HF and aluminium deposited as a back ohmic contact. Contact series resistance was not optimized in this study. Current-voltage measurements were carried out in a light-tight electrically shielded enclosure on a temperature controlled hotchuck.

III. RESULTS AND DISCUSSION

Fig. 1 shows the room temperature current-voltage characteristics of a heterojunction diode. The forward bias current density obeys the relationship $J = J_0 \exp(qV/nkT)$ where the ideality factor $n=1.2$. When diffusion current dominates, $n=1$ and when recombination dominates, $n=2$ [9]. Thus, an ideality factor of 1.2 indicates that the forward bias current is dominated by diffusion but also contains a component of recombination, most likely to occur at the SiC/Si interface. The reverse saturation current density $J_0 = 0.1\mu\text{A/cm}^2$ at room temperature and increasing temperatures reveal an activation energy for J_0 of 0.91eV.

Figure 1. Current-voltage characteristics of n-3C-SiC/p-Si heterojunction in forward and reverse bias. In forward bias, the ideality factor is 1.2 and J_0 is $0.1\mu\text{A/cm}^2$. Note the different voltage scales for reverse and forward bias.

The diode shows excellent reverse blocking characteristics, with no apparent breakdown to 200V, where the current density is 1.3mA/cm² and the rectification ratio at +/- 1V is 200,000.

Two important properties of a heterojunction diode are the reverse leakage current and breakdown voltage. Modern silicon wafers are extremely pure and hence the contribution of bandgap traps to the generation of minority carriers in the depletion region is expected to be very low compared with that of defects at the SiC/Si junction. The reverse bias current was seen not to be a linear function of $(V_{bi}+V)^{1/2}$, confirming that space charge region generation is not the dominant mechanism. Fig. 2 shows the temperature dependence of the reverse bias current, at a number of different voltages. Since the doping of the SiC is orders of magnitude higher than the silicon, most of the electric field change occurs in the silicon near the interface. It is evident that the activation energy, calculated from the slope of the reverse current versus $1/kT$ plot is not constant as the reverse bias is increased. Increasing the reverse bias from 5V to 40V results in a decrease in activation energy from 0.54eV to 0.39eV respectively. This combination of temperature and field dependence suggests that current generation is occurring via a multistep mechanism at the SiC/Si interface rather than simply trap assisted thermal generation in the silicon depletion region or at the SiC/Si interface.

Figure 2. Arrhenius plots of the reverse current density measured at different bias voltages. (a) 5V, (b) 10V, (c) 20V, (d) 40V. The activation energy is shown for each voltage.

Fig. 3 shows the band alignment of the ideal heterojunction under zero bias conditions with values of 3C-SiC bandgap and electron affinity obtained from Ref. [8]. To explain our experimental results in reverse bias, we propose a current mechanism that consists of an electron tunneling from the valence band of silicon to a trap at the SiC/Si interface followed by thermal emission into the conduction band of the SiC. As shown in Fig. 4, when the reverse bias increases from lower values (black lines) to higher values (grey lines), the tunneling process occurs at energies further from the silicon

valence band edge, thus reducing the energy required for thermal emission.

Figure 3. Band alignment diagram of the n-3C-SiC/p-Si heterojunction at zero bias.

Figure 4. Band diagram showing how different values of reverse bias produce a two-step tunneling/thermal emission process that is favored by traps of different energies.

Thus the current mechanism in reverse bias can be expressed by the following well established relationships [9]. The thermal emission time constant is governed by (1):

$$\tau_e = \tau_{e0} \cdot \exp\left[\frac{(E_{c,SiC} - E_t)}{kT}\right] \quad (1)$$

where τ_{e0} is a constant, $E_{c,SiC}$ is the SiC conduction band energy, E_t the trap energy, k is Boltzman's constant, and T is temperature.

The tunneling process time constant is governed by (2):

$$\tau_t = \tau_{t0} \cdot \exp\left(\frac{\Phi_B^{3/2}}{E_{Si}}\right) \quad (2)$$

where τ_{t0} is a constant, and E_{Si} is the electric field strength in the silicon at the heterojunction and Φ_B is the tunneling barrier height. Thus, the total time for this two step process is:

$$\tau = \tau_e + \tau_t \quad (3)$$

Whichever trap energy provides the minimum value of τ will be chiefly responsible for the reverse current density J_r , according to the following equation:

$$J_r = \frac{qN_t}{\tau} \quad (4)$$

where N_t is the trap density at that energy.

IV. CONCLUSIONS

We have demonstrated n-3C-SiC / p-Si heterojunctions with reverse bias breakdown voltages exceeding 200V, and +/-1V rectification ratio of 200,000 at room temperature. The forward bias current was found to be dominated by diffusion, with some proportion of recombination present at the SiC/Si interface as indicated by a diode quality factor of 1.2. Temperature and field dependence of the reverse diode current is explained by a trap-assisted, tunneling/thermal emission mechanism at the SiC/Si interface. Electrons tunnel from the valance band of the silicon to the most favorable trap level and are then thermally emitted to the conduction band of the SiC. As the electric field in the silicon increases with reverse bias,

the tunneling process is assisted and the energy of thermal emission is reduced. Future reduction of crystal defects at this interface will result in further improvements in reverse bias leakage currents.

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