Theoretical investigation of incomplete ionization of dopants

effect on p+nn-n+ 4H-SiC IMPATT diode

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Abstract. The effect of incomplete ionization of dopants on p+nn-n+ 4H silicon carbide (4H-SiC) impact-ionization-avalanche-transit-time (IMPATT) diodes has been investigated. Breakdown voltage, avalanche region width, DC to RF conversion efficiency and RF output power of the 4H-SiC IMPATT device with incomplete and complete ionization are given at different temperatures. Theoretical analysis reveals that the influence of the incomplete ionization of dopants on the performance of the p+nn-n+ 4H-SiC IMPATT devices cannot be ignored.

Keywords: 4H-SiC IMPATT diode, incomplete ionization, DC to RF conversion efficiency, RF power output, D-band.

1 Introduction

Impact ionization transit time (IMPATT) devices have been considered as one of the most powerful solid-state sources operating in the mm-wave and sub-mm-wave frequencies and are widely used in transmitters in radar and communication systems [1-4]. Recently, wide bandgap material SiC is one of the promising candidates in the fabrication of high-power IMPATT device because SiC exhibits excellent properties such as high breakdown voltage and high electron saturation velocity [5,6]. It is known that the impurities in 4H-SiC have relatively high value of ionization energies on the energy point of view, for example, N(45-127meV), Al(189-266meV), B (>300meV) [7-9]. So either donors or acceptors in 4H-SiC material are not completely ionized in the room temperature. The incomplete ionization of the impurities doped in the 4H-SiC can affect the characteristics of the p’n’n’+ 4H-SiC IMPATT device, such as the avalanche region width, the conversion efficiency and the RF power output. In order to obtain the higher conversion efficiency and the larger RF power output, it is essential to master the accurate knowledge of the effects of incomplete ionization of 4H-SiC. In this paper, we employ a MEDICI simulator to analysis the influence of the incomplete ionization of dopants on the breakdown voltage, the avalanche region width, the conversion efficiency and the RF power output of the p’n’n’+ 4H-SiC IMPATT device. The effect of temperature is also taken into account.
2 Simulation parameters and theoretical model

In this paper, the drift-diffusion model is used to simulate the IMPATT device because the RF power levels predicated by the drift-diffusion model and the energy modes are similar when the energy relaxation effects are low enough to be negligible at the operation frequency considered [10]. The carrier energy relaxation times of 4H-SiC material (0.02-0.03ps) is relatively low as compared to the RF signal period at D-band (5.88ps-9.09ps) [11-12]. In addition, the drift-diffusion model takes less computation time.

The energy levels of dopants in 4H-SiC are much deeper than in Si and the thermal energy ($k_bT$) is not enough to fully activate all of donor and acceptor impurity atoms at low temperatures. The ionized carrier concentration is calculated by solving the charge neutrality equation:

$$N^+_D - N^-_A + p - n = 0$$

(1)

where $N^+_D$ is ionized donors, $N^-_A$ is ionized acceptors, $p$ and $n$ are electrons and holes respectively. The ionized donors $N^+_D$ and the ionized acceptors $N^-_A$ are expressed as follows, which are related to the energy levels:

$$N^+_D = \frac{N_D}{1 + g_D \exp((E_F - E_D)/(k_bT))}$$

(2)

$$N^-_A = \frac{N_A}{1 + g_A \exp((E_F - E_A)/(k_bT))}$$

(3)

Where $g_D$ and $g_A$ are the degeneracy factors for the impurity levels, $E_F$ is the Fermi energy, $E_D$ and $E_A$ are the energy levels of donors and acceptors, respectively, and are related to activation energy ($\Delta E_D = E_C - E_D$, $\Delta E_A = E_A - E_V$). Here, $g_D = 2$, $g_A = 4$, $\Delta E_D = 0.06$, and $\Delta E_A = 0.191$ [13]. In addition, semiconductor band gap narrowing, the effect of temperature on the saturation velocity, the low field mobility, the high field mobility and the impact ionization coefficients for electrons and holes are also taken into account in the simulation [13-16].

A single-drift region with a high-low doping profile ($p^+nn^+$) is used in the simulation. The schematic diagram of 4H-SiC based high-low structure IMPATT is shown in Fig. 1, where $W$ is the total width of the depletion layer, and $x_0$ is the position of the junction. The $n^+$ and $p^+$ regions of the IMPATT device are heavily doped at $5 \times 10^{19}$ cm$^{-3}$ and the thickness is 0.2-μm of each. The $n$ region is doped at $5 \times 10^{17}$ cm$^{-3}$ and the thickness is 0.3-μm. The $n^+$ region is doped at $2 \times 10^{16}$ cm$^{-3}$ and the thickness is 0.42-μm.

![Fig.1 Schematic diagram of 4H-SiC based high-low structure IMPATT diode.](image)

3 Results and discussions

A classical set of partial differential equations comprising two continuity equations, for electrons and holes, a Poisson equation, and current density equations are solved self-consistently to obtain the DC and high frequency properties of the IMPATT device designed to operate at D-band frequencies. The variations of material parameters with temperature are incorporated in the DC and small-signal program to simulate the high-low structure IMPATT device ($p^+nn^+$) with incomplete and complete ionization effect. Fig.2 shows the breakdown voltage of the 4H-SiC IMPATT device, compared between
incomplete and complete ionizations at different temperatures. It is seen that the breakdown voltage of the IMPATT device with the incomplete ionization is always larger than those with the complete ionization. It is attributed to that the breakdown voltage of the IMPATT device is inversely proportional to the ionized impurity concentration. The number of the ionized impurity concentration in the simulation with the incomplete ionization is smaller than that with the complete ionization. Furthermore, the difference of the breakdown voltage between incomplete and complete ionizations is larger at the lower temperature range. With the increasing temperature, the changes in the breakdown voltages with the incomplete and the complete ionization decrease. It is due to that the impurity ionization rate increases with the increasing temperature at the constant doping concentration. So the number of the ionized impurity concentration in the incomplete ionization increases with the increasing temperature.

Fig 2. The breakdown voltage of the 4H-SiC IMPATT device versus temperature with effects of incomplete and complete ionizations.

Considering the temperature dependent parameters, we obtain the curves of the influence of incomplete ionization of dopants on the avalanche region width of the 4H-SiC IMPATT device, as shown in Fig.3. All the simulation results are obtained at the same current density of 44KA/cm² for the IMPATT device with incomplete and complete ionization. It is seen that the avalanche region width of the 4H-SiC IMPATT device with incomplete ionization decreases from 0.166μm to 0.151μm when the temperature increases from 300K to 400K. Then, the avalanche region width slowly increases with the increasing temperature. However, the avalanche region width with complete ionization increases with the increasing temperature in the whole temperature range. The reason is that the predominant carriers in the avalanche region near the p’n junction interface are holes in the p’n n’n’ diodes. The ionization rates of holes decrease with the increasing temperature. So the intensity of carrier multiplication around the metallurgical junction decreases with the increasing temperature. The number of the carriers is unchanged in the IMPATT device with complete ionization. In order to obtain the same current density, the avalanche region width in the IMPATT device with complete ionization would become large. But the number of the carriers for the 4H-SiC IMPATT device with incomplete ionization increases with the increasing temperature owning to that the ionized impurity concentration increases with the increasing temperature. The increasing ionized impurity concentration and the decreasing ionization rates of holes in the IMPATT device with incomplete ionization would lead to that the avalanche region width of the 4H-SiC IMPATT device with incomplete ionization first increases, then decreases at the same current density.
Fig. 3. The avalanche region width of the 4H-SiC IMPATT device versus temperature with effects of incomplete and complete ionizations.

It is plotted that the DC to RF conversion efficiency of the 4H-SiC IMPATT devices with incomplete and complete ionization as a function of the temperature in Fig. 4. It is observed from Fig. 4 that the DC to RF conversion efficiency of the device with complete ionization decreases with the increasing temperature, while the conversion efficiency of the device with incomplete ionization first increases when the temperature increases from 300K to 400K, then decreases with the increasing temperature. It is known that the wider avalanche region results in the larger avalanche region voltage drop and the lower DC to RF conversion efficiency in the IMPATT device [17]. So the variation trend of the conversion efficiency with the temperature for the IMPATT device with incomplete and complete ionization is opposite to the variation of the avalanche region width with the temperature. We found that the optimal operating temperature range at which the higher conversion efficiency is obtained is different for the IMPATT device with incomplete and complete ionization. From this point of view, the effect of incomplete ionization of dopants cannot be ignored in the p‘nn+p 4H-SiC IMPATT device.

Fig. 4. The DC to RF conversion efficiency of the 4H-SiC IMPATT device versus temperature with effects of incomplete and complete ionizations.

Fig.5 presents that the output power density of the IMPATT device with incomplete and complete ionization at different temperature. The output power density of the IMPATT device with complete ionization decreases with the increasing temperature. The output power density of the IMPATT device with incomplete ionization increases from 300k to 400k, then decreases with the increasing temperature. The results are caused by the breakdown voltage and the DC to RF conversion efficiency due to that the output power is proportional to both of them ($P_{out} = I_{dc} \cdot V_B, P_{out} = \eta \times P_{in}$).
Fig. 5. The output power density of the 4H-SiC IMPATT device versus temperature with effects of incomplete and complete ionizations.

4 Conclusion
In conclusion, we have investigated the influence of the incomplete ionization on breakdown voltage, avalanche region width, conversion efficiency and RF power output of the p’nn’n+ 4H-SiC IMPATT diodes though the MEDICI simulation platform. The effect of the incomplete ionization of dopants on the performance of the IMPATT device cannot be ignored. The results show that the optimal operating temperature ranges at which the higher DC to RF conversion efficiency is obtained for the p’nn’n+ 4H-SiC IMPATT device with incomplete and complete ionization are different. It is obvious that the p’nn’n+ 4H-SiC IMPATT diode is suitable for applying in the higher temperature range compared with the Si and GaAs IMPATT diode. The results will be help to design the heat sink of the p’nn’n+ 4H-SiC IMPATT diode to obtain higher DC to RF conversion efficiency and larger RF output power.

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