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Fabrication and characteristics of lateral Ti/4H-SiC Schottky barrier diodes*

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This paper describes the fabrication and characteristics of the lateral Ti/4H-SiC Schottky barrier diodes (SBDs). SBDs are fabricated by nitrogen ion implantation into p-type 4H-SiC epitaxial layer. The implant depth profile is simulated using the Monte Carlo simulator TRIM. Measurements of the reverse I–V characteristics demonstrate a low reverse current, that is good enough for many SiC-based devices such as SiC metal-semiconductor field-effect transistors, and SiC static induction transistors. The parameters of the diodes are extracted from the forward I–V characteristics. The barrier height $\phi_{\rm b}$ of Ti/4H-SiC is 0.95 eV.

Keywords: silicon carbide, ion implantation, Schottky barrier diodes, barrier height
PACC: 7280J, 7630D, 7155D, 7850G

1. Introduction

Silicon carbide (SiC)[1] has outstanding properties such as wide bandgap, high breakdown field and saturation–electron drift velocity, and has been used to fabricate high-temperature, high-power, and high-speed devices. Schottky contacts are very important in semiconductor devices and integrated circuits. Hence many authors have investigated the properties of SiC Schottky barrier diodes (SBDs) such as Ni, Pt/4H, 6H-SiC,[2] Ti/4H-SiC,[3] Co/6H-SiC,[4] and Pt/6H-SiC[5], etc. Generally speaking, all of the papers mentioned above focus on the vertical SBD (whose ohmic contacts are on the back side of the substrate), which has a different structure from that of metal-semiconductor field-effect transistors (MESFETs). Lateral SBD is the key part of MESFETs and is also important for integrated circuits (ICs). It is urgent to form a good characteristic lateral SBDs. Ions implantation of dopants has been recognized as a crucial means of selective area doping because the thermal diffusion rates of most dopants are very slow in SiC at temperatures lower than 1800–2000°C. The lateral 4H-SiC SBDs are formed on n-type layer obtained by nitrogen ions implantation. There have been few reports on Schottky contacts of nitrogen implanted 4H-SiC.

In this paper we report the lateral Schottky barrier contact formation of 4H-SiC and its characteristics, and describe the fabrication process of Ti/silicon face 4H-SiC in detail. The I–V characteristics of the sample is also investigated and simulated.

2. Experiment

The structure of SBD investigated in this paper is shown in Fig.1. The Schottky contact area is $80\times150\mu{\rm m}^2$ ($1.2\times10^{-4}{\rm cm}^2$), which is equal to the N^+ region. The SBDs are fabricated on silicon face 4H-SiC purchased from Cree Research. The substrate is of a highly doped n-type structure ($N_{\rm d}$=$7.1\times10^{18}{\rm cm}^{-3}$) with a lightly doped p-type epitaxial layer (1.8μm $N_{\rm a}$=$6.5\times10^{15}{\rm cm}^{-3}$). N-wells are formed by three times nitrogen ions implantation after the die are deposited 450 nm SiO_2 by low-pressure chemical vapour deposition (LPCVD) and patterned, while N^+ regions for ohmic contacts are formed by a high-dose nitrogen ions implantation in the same way. All implantations are performed at 500°C. After chemically cleaned in the buffer agent of hydrofluoric acid, the sample is an-

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nealed at 1480°C for 30 min in pure argon atmosphere. Both the ohmic and Schottky contacts on the surface are patterned through conventional photolithography and lift-off techniques. Ohmic contact windows on the LPCVD SiO_2 film are first formed, and Ni/Cr and Au are evaporated separately and alloyed at 900°C for 30 min in a vacuum furnace to realize ohmic contacts. Finally, Schottky contacts are realized by evaporating Ti/Pt/Au after SiO_2 is patterned.

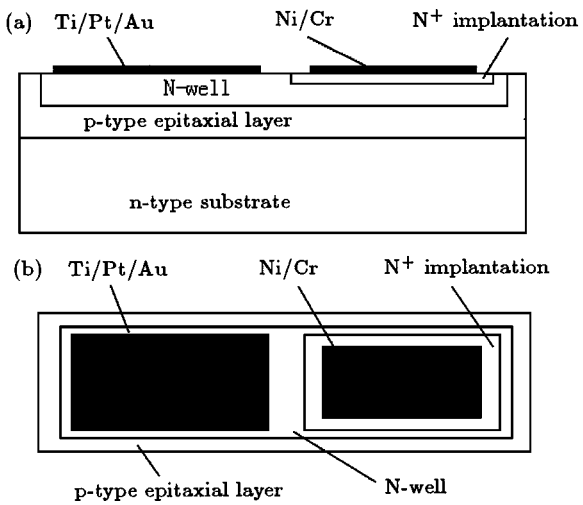


Fig.1. (a) Schematic cross section of 4H-SiC SBDs, (b) top view of 4H-SiC SBDs.

Nitrogen ions in the N-well region are implanted at energies and doses of 55 keV, $1.07\times10^{13}\mathrm{cm}^{-2}$, 100 keV, $1.53\times10^{13}\mathrm{cm}^{-2}$, and 160 keV, $1.95\times10^{13}\,\mathrm{cm}^{-2}$. The sample is then repatterned with resist before being implanted with high-dose nitrogen ions at energy and dose of 30 keV, $3.54\times10^{14}\mathrm{cm}^{-2}$. The location of peak concentration and the longitudinal straggling of N ions are calculated using the Monte Carlo simulator TRIM.[6] Fig. 2 shows the ion-implantation profiles using the Gaussian model for expressing the ion-implantation ranges.

A previous experiment by Handy *et al*[7] indicated that a 15 min implant activation at 1500°C results in 15% nitrogen activation. Seshadri *et al*[8] obtained 6.3% activation by 1300°C annealing. The die in this work is annealed at 1480°C for 30 min in an argon atmosphere. The activation of N is about 10% under this condition. The implant profile shown in Fig.2 is expected to result in an effective doping concentration of $1.5\times10^{17}\mathrm{cm}^{-3}$.

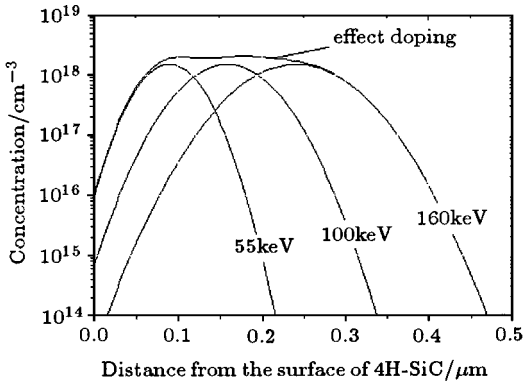


Fig.2. Simulated ion-implantation profiles for N ions implanted into 4H-SiC.

3. Results and discussion

The I–V measurements are performed with an HP4156B semiconductor parameter analyser. Figure 3 exhibits the I–V characteristics curve, showing a low reverse current ($1\times10^{-4}\mathrm{A\cdot cm}^{-2}$).

Using the thermionic emission theory, the current running through the SiC Schottky diode can be expressed as

$$I = AA^*T^2\exp\left(-\frac{\phi_b}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right)-1\right], \qquad (1)$$

where A is the diode area, A^* is the Richardson's constant, ϕ_b is the Schottky barrier height, n is the ideality factor, and other constants have their usual meanings. At a low forward voltage, the ideality factor can be given by

$$n = \frac{q}{kT}\frac{\partial V}{\partial \ln I}. \qquad (2)$$

If the forward voltage is larger than the threshold voltage, Eq.(1) becomes

$$I = AA^*T^2\exp\left(-\frac{\phi_b}{kT}\right)\left\{\exp\left[\frac{q}{nkT}(V-IR_\mathrm{s})\right]-1\right\}, \qquad (3)$$

where

$$R_\mathrm{s} = \left(1-\frac{\partial \ln I}{\partial V}\frac{nkT}{q}\right)\Big/\left(\frac{\partial I}{\partial V}\right) \qquad (4)$$

is the series resistance.

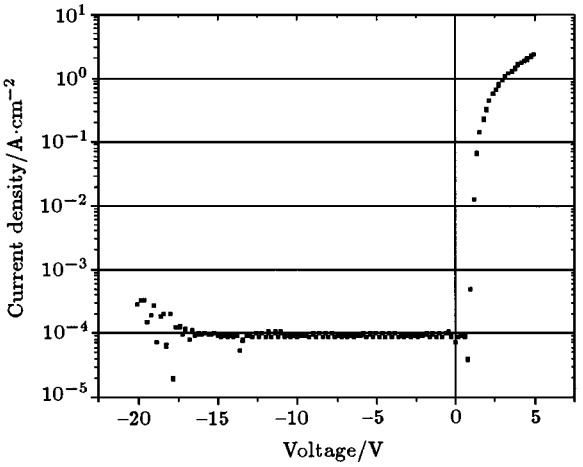


Fig.3. I–V characteristics of Ti/4H-SiC Schottky diodes.

The parameters of the 4H-SiC SBDs are $A = 1.2 \times 10^{-4}$cm^2, A^*=150A·cm^{-2}K^{-2}.[9] Using the thermionic emission model mentioned above, the ideality factor n=3.0, the series resistance R_s=11.9kΩ. Figure 4 shows the experimental measurements in terms of this model. A good agreement between experiments and the thermionic emission model is observed. From the y-intercept of the linear region of the I–V curves, the barrier height of Ti/silicon face 4H-SiC ϕ_b=0.95V can be obtained, a value which is consistent with that in Ref.[10].

The ideality factor n is larger due to the interface states of the SBDs.[11] Residual defects[12] and surface roughening[13,14] are caused by ion implantation and annealing. The surface of 4H-SiC in this work is not particularly smoothed to reduce the interface state density. A proper, etching condition can produce extremely smooth surface,[15] which will make the ideality factor n close to unity.[16]

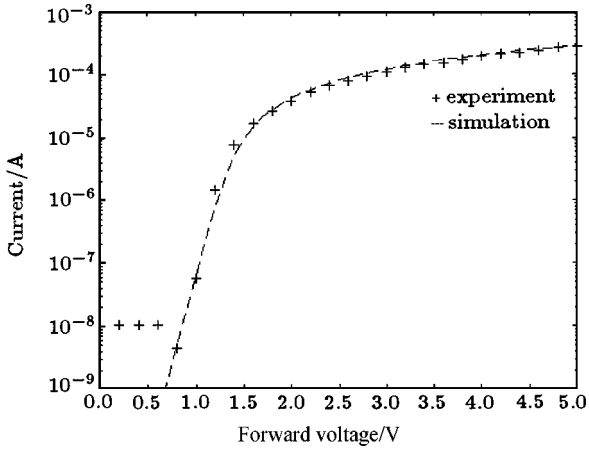


Fig.4. Comparison between the thermionic emission current model and experimental results for the forward I–V characteristics of Ti/4H-SiC SBDs.

4. Conclusions

The process of fabrication methods of the lateral Ti/4H-SiC SBDs has been described in detail. We have examined the electrical properties of the diodes by I–V measurements and found excellent behaviours of the reverse current–voltage characteristics. The barrier height of Ti/silicon face 4H-SiC SBDs is found to be 0.95 eV from the forward I–V characteristics.

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