Characterization of ion-implanted 4H-SiC Schottky barrier diodes

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Ion-implantation layers are fabricated by multiple nitrogen ion-implantations (3 times for sample A and 4 times for sample B) into a p-type 4H-SiC epitaxial layer. The implantation depth profiles are calculated by using the Monte Carlo simulator TRIM. The fabrication process and the I–V and C–V characteristics of the lateral Ti/4H-SiC Schottky barrier diodes (SBDs) fabricated on these multiple box-like ion-implantation layers are presented in detail. Measurements of the reverse I–V characteristics demonstrate a low reverse current, which is good enough for many SiC-based devices such as SiC metal–semiconductor field-effect transistors (MESFETs), and SiC static induction transistors (SITs). The parameters of the diodes are extracted from the forward I–V and C–V characteristics. The values of ideality factor n of SBDs for samples A and B are 3.0 and 3.5 respectively, and the values of series resistance $R_{\rm s}$ are 11.9 and 1.0 kΩ respectively. The values of barrier height $\phi_{\rm B}$ of Ti/4H-SiC are 0.95 and 0.72 eV obtained by the I–V method and 1.14 and 0.93 eV obtained by the C–V method for samples A and B respectively. The activation rates for the implanted nitrogen ions of samples A and B are 2% and 4% respectively extracted from C–V testing results.

Keywords: silicon carbide, ion-implantation, Schottky barrier diodes, barrier height

PACC: 7280J, 7630D, 7155D, 7850G

1. Introduction

Silicon carbide (SiC)[1] is a wide bandgap semiconductor material. Owing to its outstanding properties such as high breakdown field, great thermal conductivity and high saturation-electron drift velocity, it has been used to fabricate high-power, high-temperature, and high-speed devices. Ion-implantation is a key process for the fabrication of semiconductor devices. For SiC materials, ion-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. Ion-implanted MESFETs show low cost in production,[2] low noise,[3−5] high speed[6,7] and planarity without mesa etching due to the creation of the active device region by the ion-implantation technique. An ion-implanted channel of MESFETs is more controllable to form thinner and more highly doped channel layers than those fabricated with conventional epitaxial growth, so it can improve the radio frequency (RF) characteristics of MESFETs. References [8] and [9] reported on the fabrication of a 2 μm gate length ion-implanted 4H-SiC MESFET with the source, the drain and the channel regions made by ion-implantation. Recently, a 0.5 μm gate 4H SiC MESFET on semi-insulating (SI) substrate was fabricated by using ion-implantation for the channel and contact regions and had the same electrical characteristics as the epitaxial SiC MESFET.[10]

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,[11] Ti/4H-SiC,[12] Co/6H-SiC,[13] Pt/6H-SiC,[14] and their structures for high voltage power devices,[15,16] etc. Ion-implantation is often used to make guard rings for SBDs, which have lower leakage current and higher breakdown voltage.[17] Generally speaking, all of the papers mentioned above focused on vertical SBDs (whose ohmic contacts are on the back side of the substrate), which have different structures from those of metal–semiconductor field-effect transistors (MESFETs). Lateral SBDs are the key parts of MESFETs and are also important for integrated circuits (ICs), so it is urgently needed to form a good characteristic lateral SBD. There have been

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few reports on lateral SBDs formed on n-type layers obtained by multiple nitrogen ion-implantations.

In the present paper lateral Ti/silicon face 4H-SiC SBDs formed on the multiple box-like ion-implanted layers are investigated. The active regions of two samples A and B are obtained by implanting nitrogen ions 3 and 4 times respectively. I–V and C–V characteristics of the ion-implanted Ti/4H-SiC SBDs are given. The series resistances $R_{\rm s}$ and the ideality factor n are extracted from the forward I–V characteristics. The values of barrier height $\phi_{\rm B}$ of the lateral SBDs are obtained from I–V and C–V curves separately. The activation rates of implanted ions are given finally.

2. Fabrication process

The substrate of 4H-SiC in this study is of a highly doped n-type structure with a donor density of 7.1×10^{18} cm^{-3} and the epitaxial layer is 1.8 μm with an acceptable light dopant density of 6.5×10^{15} cm^{-3}. The structure of lateral SBDs investigated is shown in Fig. 1, which is the same as that we obtained before.[18] N-wells of samples A and B are formed by implanting nitrogen ions 3 and 4 times after the dies have been coated by a 450 nm thick SiO_2 layer by low-pressure chemical vapour deposition (LPCVD) and patterned, while N^+ regions for ohmic contacts are formed by a high-dose nitrogen ion-implantation in the same way. All implantations are performed at 500 °C. After being chemically cleaned in a buffer agent of hydrofluoric acid, samples A and B are annealed at 1480 °C and 1650 °C respectively for 30 minutes in pure argon atmosphere. The channel depth is mainly determined by the times of implantation and the activation rate is dependent on the annealing temperature. In order to gain more information from the SBDs fabricated, two samples are annealed at different temperatures.

Both the ohmic and the 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, SBDs are realized by evaporating Ti/Pt/Au after the SiO_2 film has been patterned. The metal Ti is the first layer on silicon face 4H-SiC with metal Au as a pad outside.

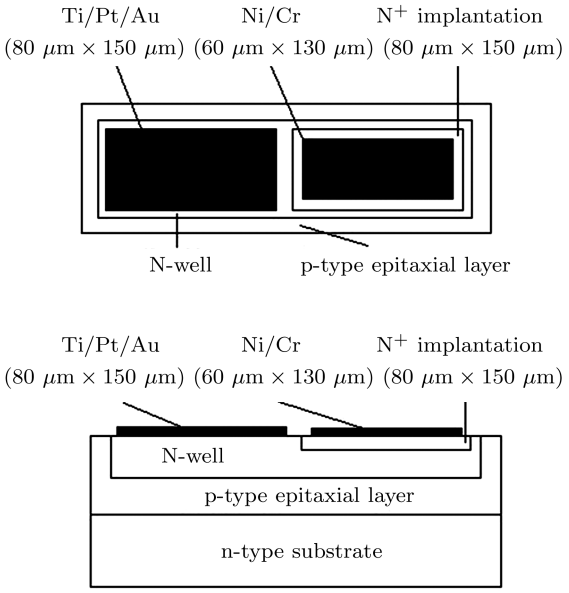


Fig. 1. Top view (top) and schematic cross section (bottom) of 4H-SiC SBDs.

Nitrogen ions implanted in the N-well region designed for sample A are at energies and doses of 55 keV and 1.07×10^{13} cm^{-2}, 100 keV and 1.53×10^{13} cm^{-2}, and 160 keV and 1.95×10^{13} cm^{-2}, respectively, and for sample B are at 55 keV and 1.07×10^{13} cm^{-2}, 100 keV and 1.53×10^{13} cm^{-2}, 160 keV and 1.95×10^{13} cm^{-2}, and 240 keV and 2.34×10^{13} cm^{-2} respectively. Two samples are then repatterned with resist before being implanted with high-dose nitrogen ions in the ohmic contact region at an energy and dose of 30 keV and 3.54×10^{14} cm^{-2} respectively. The location of peak concentration and the longitudinal straggling of nitrogen ions are calculated by using the Monte Carlo simulator TRIM.[19] The concentration of implanted nitrogen ions in the N-well is designed to be 1.5×10^{18} cm^{-3}. The effective doping of the active layer depends on the activation rate of the nitrogen ions.

3. Results and discussion

3.1. I–V characteristics

The I–V measurements are performed with an HP4156B semiconductor parameter analyser. Figure 2 exhibits the I–V characteristics curve, showing a low reverse current (1×10^{-4}A· cm^{-2}). Using the thermionic emission theory, the current flowing through the SiC SBDs can be expressed as

$$I = AA^*T^2 \exp\left(-\frac{q\phi_{\rm B}}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right)-1\right], \quad (1)$$

where A is the diode area, A^* is Richardson's constant, $\phi_{\rm B}$ 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

$$n = \frac{q}{kT}\frac{\partial V}{\partial \mathrm{In}I}. \tag{2}$$

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

$$I = AA^*T^2 \exp\left(-\frac{q\phi_{\rm B}}{kT}\right) \times \left\{\exp\left[\frac{q}{nkT}(V - IR_S)\right] - 1\right\}, \tag{3}$$

where

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

is the series resistance.

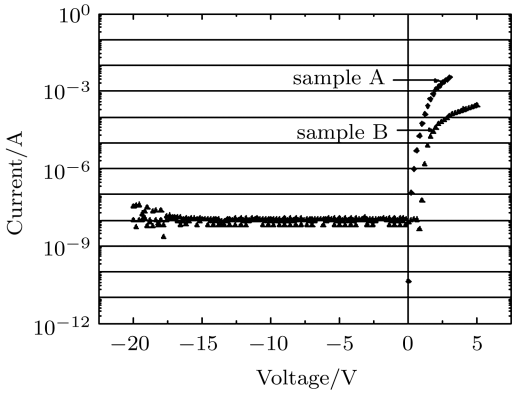


Fig. 2. I–V characteristics of Ti/4H-SiC SBDs for sample A and sample B.

The parameters of the 4H-SiC SBDs are $A = 1.2 \times 10^{-4}$ cm^2, $A^* = 150$ A·cm$^{-2}\cdot$K^{-2}.[20] Using the thermionic emission model mentioned above, the values of ideality factor n of the 4H-SiC SBDs are 3.0 for sample A and 3.5 for sample B. The values of series resistance $R_{\rm s}$ of the 4H-SiC SBDs are 11.9 and 1.0 kΩ for samples A and B respectively. Figure 3 shows the experimental measurements and the calculation lines by using this model. The measurements and the calculations from the thermionic emission model are found to be in good agreement with each other. From the y-intercept of the linear region of the I–V curves, values of the barrier height $\phi_{\rm B}$ of Ti/silicon face 4H-SiC of 0.95 eV and 0.72 eV for samples A and B can be obtained respectively, which are consistent with those on the epitaxial growth doping layer in Ref. [21].

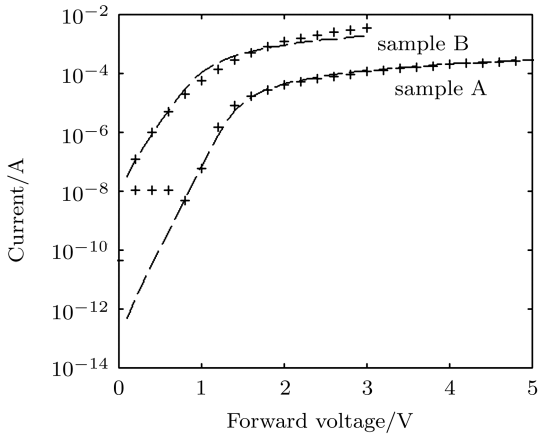


Fig. 3. Comparison between results from the thermionic emission current model and measurements for the forward I–V characteristics.

The ideality factor n is larger due to the interface states of the SBDs.[22] Residual defects[23] and surface roughness[24,25] 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. An appropriate etching condition can produce an extremely smooth surface,[26] which will make the ideality factor n close to unity.[27]

3.2. C–V characteristics

From the one-dimensional Poisson equation, the concentration of donors $N_{\rm d}(d)$ at the depth d from the surface of 4H-SiC can be expressed as[28]

$$N_{\rm d}(d) = \frac{C^3}{q\varepsilon_0\varepsilon_{\rm s}A^2}\left(\frac{{\rm d}C}{{\rm d}V}\right)^{-1}, \tag{5}$$

where

$$d = \frac{\varepsilon_0\varepsilon_{\rm s}}{C}, \tag{6}$$

C is the capacitance of SBDs, $\varepsilon_{\rm s}$ is the permittivity of 4H-SiC, and A is the area of 1.2×10^{-4} cm^2 of SBDs in this study, $N_{\rm d}(d)$ here is the concentration of activated donors of the ion-implanted layer after high temperature annealing. The small signal ac capacitance as a function of applied voltage (C–V characteristics) at 1 MHz is measured. The C^{-2}–V characteristics of SBDs are given in Fig. 4.

The concentrations of activated donors $N_{\rm d}(d)$ are calculated from expression (5) to be 3.0×10^{16} and 6.0×10^{16} cm^{-3} for samples A and B respectively. The design concentration of implanted nitrogen ions is 1.5×10^{18} cm^{-3}, so the activation rates for samples A and B are 2% and 4% respectively.

The barrier height of SBDs can be expressed as[21]

$$\phi_{\rm B} = V_{\rm bi} + V_{\rm n} + kT/q, \tag{7}$$

where

$$V_{\rm n} = \frac{kT}{q}{\rm In}\left(\frac{N_{\rm c}}{N_{\rm d}}\right) \tag{8}$$

is the band gap between the bottom of the conductive band and the Fermi energy, $V_{\rm bi}$ is the built-in voltage of the SBDs and is the intercept on the x-axis in Fig. 4, $N_{\rm c}$ is the effective density of electrons of the conduction band, and $N_{\rm d}$ is the donor concentration.

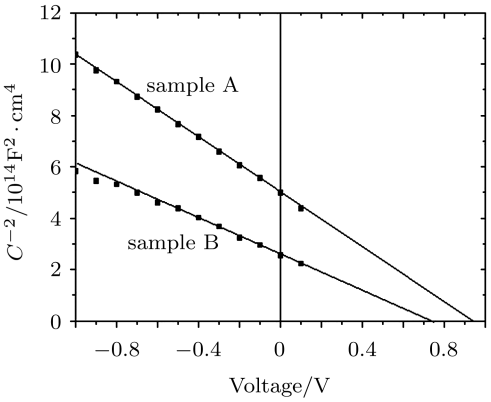


Fig. 4. C^{-2}–V characteristics of Ti/4H-SiC SBDs for sample A and sample B.

The values of $V_{\rm n}$ calculated from expression (8) are 0.18 and 0.16 eV for 4H-SiC SBDs of the samples A and B respectively, the values of $V_{\rm bi}$ from Fig. 4 are 0.93 and 0.74 eV, so the barrier heights from the C–V characteristics of the Ti/4H-SiC SBDs for the two samples are 1.14 and 0.93 eV respectively.

3.3. Discussion

The lower values 2% and 4% of the activation rate suggest that a higher implantation temperature above 500 °C and a higher annealing temperature above 1650 °C[29,30] are required to receive a significant activation rate. High temperature (600,[24] 700,[29] and 1000 °C[30]) implantations are used to prevent amorphization.[31]

In the same annealing time, the activation rate of the implanted nitrogen ions rises with increasing annealing temperature as indicated from the experiment in Ref. [32]. But the change becomes flat when the annealing temperature is higher than 1700 °C. A previous experiment[29] indicated that a 15 min implant activation at 1500 °C resulted in 15% nitrogen activation. In Ref. [30] the activation by annealing at 1300 °C was achieved to be 6.3%, and the activation by annealing at temperatures above 1500 °C for nitrogen was realized to be almost complete. As a contrast, an experiment carried out later in Ref. [33] indicated that a 15 min implantation activation at 1500 °C resulted in 3% of nitrogen activation.

The heat treatment of post implantation is also for reducing defects caused by the implantation.[34] However, a high annealing temperature would cause a lot of large black spots.[23] In Ref. [35] the annealing conditions for implanted phosphorus ions were investigated and the precipitation of phosphorus and the evaporation of the implanted layer from a long annealing time, causing the sheet resistance to increase, were found, thus indicating that rapid thermal annealing at high temperatures for a short time was needed. So short time annealing techniques such as flash lamp annealing[36] and rapid isothermal annealing (RIA)[37] are needed because they can reach 2000 °C for about 20 ms and can obtain a high electrical activation rate and further defect removal compared with the traditional furnace annealing. Solid-state microwave[38] annealing is capable of providing a temperature rise rate of 600 °C/s and a fall rate of 400 °C/s, which avoids a high degree of sublimation caused by conventional furnace annealing.

In order to reduce the surface roughness[25] and the loss of dopants under the high annealing temperature, a SiC coated graphite crucible[23] is used to contain the annealing sample and a dummy SiC wafer[39] is placed on the sample. In Ref. [29] an AlN encapsulant layer was used to prevent the SiC surface from being damaged during the high temperature annealing. Here we place a semi-insulating (SI) SiC wafer on the implanted SiC surface during annealing (the so called face-to-face technique). A graphite cap[38] used in rapid microwave annealing in a temperature range of 1750–1900 °C for 30 s has a low surface roughness of 2.4 nm. A comparison between AlN/BN and graphite annealing caps was made in Ref. [40]. Both of them show the ability to prevent the silicon diffusing out of SiC and they were able to be easily removed after annealing when their temperature was less than 1800 °C. AlN could not be completely etched away after 1800 °C annealing, so the surface would be rougher. The graphite cap could be easily removed by an oxygen plasma for most annealing temperatures, but the out-diffusion of silicon is most severe at 1800 °C, where it roughens the SiC surface and forms reaction products when the Si reacts with the graphite at a significant rate.

Thus it can be seen the activation of ions depends on not only the annealing temperature but also conditions such as the implantation temperature, the rising and the falling time of temperature, the environmental

conditions, etc. In the future work, high-temperature implantation, rapid thermal annealing and the surface protection technique will be used to achieve a perfect SiC implantation layer.[41]

4. Conclusions

An active region fabricated by ion-implantation has great features, and it has the potential to realize planar high frequency MESFETs. Multiple nitrogen ion-implantations into 4H-SiC are investigated. Multiple ion-implantation into two samples A (with implanting ions 3 times) and B (with implanting ions 4 times) is carried out. The method of fabricating the lateral Ti/4H-SiC SBDs on the ion-implanted layers is described in detail. We examine the electrical properties of these diodes by I–V and C–V measurements. Ion-implanted Ti/4H-SiC SBDs show excellent behaviours of the reverse current-voltage characteristics. The values of ideality factors n are 3.0 and 3.5 for samples A and B from the thermionic emission model. The values of series resistance $R_{\rm s}$ are 11.9 kΩ for sample A and 1.0 kΩ for sample B. The values of barrier height $\phi_{\rm B}$ of Ti/silicon face 4H-SiC SBDs are found to be 0.95 and 0.72 eV from the forward I–V characteristics and 1.14 and 0.93 eV from C–V characteristics for samples A and B respectively.

References

[1] Ostling M, Lee H S, Domeij M and Zetterling C M 2006 *Int. Conf. Mixed Design* p34

[2] Watanabe M, Fukushi D, Yano H and Nakajima S 2007 *CS Mantech Conf.* p187

[3] Onodera K, Nishimura K, Aoyama S and Sugitani S 1999 *IEEE Trans. Electron Devices* **46** 310

[4] Feng M, Scherrer D R, Apostolakis P J and Kruse J W 1996 *IEEE Trans. Electron Devices* **43** 852

[5] Danzilio C 1998 *Proc. Conf. GaAs Manufact. Technol.* p111

[6] Feng M, Law C L, Eu V and Ito C 1991 *Appl. Phys. Lett.* **59**(19) 1233

[7] Tang H Z, Caruth D and Becher D 1999 *IEEE Electron Device Lett.* **20** 245

[8] Tucker J B, Mitra S, Papanicolaou N and Siripuram A 2002 *Diam. Rel. Mater.* **11** 392

[9] Tucker B, Papanicolaou N, Rao M V and Holland O W 2002 *Diam. Rel. Mater.* **11** 1344

[10] Katakami S, Ogata M, Ono S and Arai M 2007 *Mater. Sci. Forum* **556–557** 803

[11] Saxena V, Su J N and Steckl A J 1999 *IEEE Trans. Electron Devices* **46** 456

[12] Defives D, Noblanc O, Dua C and Brylinski C 1999 *IEEE Trans. Electron Devices* **46** 449

[13] Lundberg N and Ostling M 1993 *Appl. Phys. Lett.* **63** 3069

[14] Bhatnagar P, McLarty K and Baliga B J 1992 *IEEE Electron Device Lett.* **13** 501

[15] Karoui M B, Gharbi R, Alzaied N and Fathallah M 2008 *Materials Science and Engineering* **28** 799

[16] Hull B A, Sumakeris J J, O'Loughlin M J and Zhang Q 2008 *IEEE Trans. Electron Devices* **55** 1864

[17] Frey W L and Ryssel H 2001 *Applied Surface Science* **184** 413

[18] Wang S G, Yang L A, Zhang Y M, Zhang Y M, Zhang Z Y and Yan J F 2003 *Chin. Phys.* **12** 322

[19] Gerritsen E, Keetels H A A and Ligthart H J 1989 *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **39** 614

[20] Itoh A, Kimoto T and Matsunami H 1995 *IEEE Electron Devices Lett.* **16** 280

[21] Itoh A and Matsunami H 1997 *Phys. Stat. Sol.* (a) **162** 389

[22] Card H C and Rhoderick E H 1971 *J. Phys.* D: *Appl. Phys.* **4** 1589

[23] Ohno T, Onose H and Sugawara Y 1999 *J. Electron Mater.* **28** 1801

[24] Capano M A, Ryu S and Melloch M R 1998 *J. Electron Mater.* **27** 370

[25] Capano M A, Ryu S and Cooper J A 1999 *J. Electron Mater.* **28** 214

[26] Wang J J, Lambers E S, Pearton S J and Ostling M 1998 *Solid State Electron.* **42** 2283

[27] Constantinidis G, Kuzmic J, Michelakis K and Tsagaraki K 1998 *Solid State Electron.* **42** 253

[28] Chen M and Wang J N 1999 *Basic Material Physics for Semiconductor Devices* (Beijing, China: Science Press) **5**(1) p283 (in Chinese)

[29] Handy E M, Rao M V and Jones K A 1999 *J. Appl. Phys.* **86** 746

[30] Seshadri S, Eldridge G W and Agarwal A K 1998 *App. Phys. Lett.* **72** 2026

[31] Yang Z D, Du H H and Libera M 1996 *J. Mater. Res.* **10** 1441

[32] Capano M A, Santhakumar R and Das M K 1999 *Electron. Mater. Conf.* p210

[33] Rao M V, Tucker J and Holland O W 1999 *J. Electron Mater.* **28** 334

[34] Abe K, Ohshima T and Itoh H 1998 *Mater. Sci. Forum* **264–268** 721

[35] Senzaki J, Fukuda K and Arai K 2003 *J. Appl. Phys.* **94** 2942

[36] Anwand W, Brauer G and Panknin D 2001 *Mater. Sci. Forum* **363–365** 442

[37] Pankin D, Wirth H and Anwand W 2000 *Mater. Sci. Forum* **338–342** 877

[38] Sundaresan S G, Mahadik N A, Qadri S B and Schreifels J A 2008 *Solid State Electron.* **52** 140

[39] Kimoto T, Takemura O and Matsunami H 1998 *J. Electron Mater.* **27** 358

[40] Jones K A, Wood M C, Zheleva T S and Kirchner K W 2008 *J. Electron Mater.* **37** 917

[41] Wang S G, Zhang Y M and Zhang Y M 2003 *Chin. Phys.* **12** 89