Fabrication of Ti ohmic contact to n-type 6H-SiC without high-temperature annealing*

Chang Shao-Hui(常少辉), Liu Xue-Chao(刘学超)†, Huang Wei(黄 维), Xiong Ze(熊 泽), Yang Jian-Hua(杨建华), and Shi Er-Wei(施尔畏)

Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, *China*

(Received 9 February 2012; revised manuscript received 2 March 2012)

The effect of surface morphology of 6H-SiC substrate on the ohmic contact properties of Ti/6H-SiC structure is studied. The H-terminated surface on Si-face 6H-SiC is obtained by both dipping SiC into HF acid solution for 15 s and thermal heating SiC in hydrogen atmosphere at 1100 °C for 10 min, while the H-terminated surface on C-face 6H-SiC could be obtained only by the latter method. Ti is deposited on Si-face and C-face SiC substrates with H-terminated surfaces and ohmic contact is obtained without high-temperature annealing.

Keywords: Ti contact, 6H-SiC, HF acid, H_2 treatment

PACS: 68.55.ag, 73.40.Cg **DOI:** 10.1088/1674-1056/21/9/096801

1. Introduction

Silicon carbide (SiC) is regarded as an excellent candidate for high power, high frequency, and high temperature electronic devices due to its excellent physical properties such as wide band gap, high breakdown field, high thermal conductivity, and high saturation electron velocity.[1] Recent progress in the high-quality large-scale SiC single crystal and epitaxial technology has promoted the applications of SiC-based devices.[2,3] As is well known, metallization is one of the most important processes in the fabrication of electronic devices. The conventional approaches to obtaining ohmic contact to silicon (Si) are ion implantation and thermal diffusion. However, such methods are restricted in the fabrication of ohmic contact to SiC by low electrical activity and very high annealing temperature.[4,5] At present, the metal/SiC ohmic contact is usually prepared by depositing nickel thin film followed by high-temperature annealing (typically around 1000 °C) in argon (Ar) atmosphere.[6] However, the anneal process often restricts the device fabrication and makes the electrode rough.[7,8] Hara *et al.*[9,10] obtained ohmic contact on Si-face SiC by controlling Fermi level pinning, but no further comprehensive study was performed. Although most of the metal/SiC studies were focused on the Si-face, the ohmic contact to the wafer backside is also important especially for the vertical power devices.[11]

In this study, the ohmic contacts to both of the Si-face and C-face are studied. Titanium (Ti) is selected as the contact metal due to its low work function. We concentrate on the effect of surface morphology on the contact properties of Ti/SiC structure. It is found that both hydrofluoric (HF) acid solution dipping and hydrogen thermal treatment can avoid heavy impurity doping and high-temperature annealing in fabricating ohmic contact to the n-type 6H-SiC substrate.

2. Experiment

The SiC ingots were grown by home-made physical vapour transport equipment in the Laboratory of Silicon Carbide, Shanghai Institute of Ceramics. The SiC ingots were oriented by X-ray direction finder and then cut by wire saw. All the wafers are n-type {0001} (Si-face and C-face) on-axis 6H-SiC. The electrical properties were measured by a Hall effect measurement system. The resistivity is $\sim$ 55.1 mΩ·cm and the electron concentration is 7.8×10^{17} cm^{-3}. Three 2-inch SiC wafers were mechanically polished on the (0001) Si-face with 2.5 μm diamond slurry for 2 h. One wafer was selected and referred to as type 1. The

*Project supported by the Innovation Program of the Chinese Academy of Sciences (Grant No. KJCX2-EW-W10), the Shanghai Municipal Science and Technology Commission, China (Grant Nos. 09DZ1141400 and 09520714900), and the Young Scientists Fund of the National Natural Science Foundation of China (Grant No. 51002176).

†Corresponding author. E-mail: xcliu@mail.sic.ac.cn

© 2012 Chinese Physical Society and IOP Publishing Ltd

other two wafers were further polished with 0.25 μm diamond slurry for 2 h, and then one wafer was selected and named type 2. Finally, the last wafer was polished by chemical–mechanical polishing (CMP) using colloidal silica slurry with a pH of 10.4 at 60 revolutions per minute and pressure of 350 g/cm^2 for 6 h and called type 3. The type 4 sample was processed on a (000−1) C-face 6H-SiC using the same procedure as that for type 3. All the wafers were cleaned as follows: First, the wafers were ultrasonically cleaned in acetone for 10 min to remove the organic contamination from the sample surface and rinsed with deionized water 10 times. The next step is performed with a boiled solution of NH_4OH (ammonium hydroxide), H_2O_2 (hydrogen peroxide), and H_2O (water) with a ratio of 1:1:6 for 15 min. Then the samples were rinsed with deionized water 10 times. After that, the samples were cleaned with a boiled solution of hydrochloric acid (HCl), H_2O_2, and H_2O with a ratio of 1:1:6 for 15 min. With this treatment, the remaining traces of metallic (ionic) contaminants could be effectively removed. Then the samples were rinsed with deionized water 10 times. Before depositing Ti on SiC, all the wafers were immersed in buffered HF solution for 15 s, followed by deionized water immersion for 5 min and finally dried by high-purity N_2. Two more wafers with type 3 and type 4 procedures were polished and cleaned, and then were treated by hydrogen (H_2) gas at 1100 °C for 10 min in a hot wall chemical vapour deposition system, which were named type 5 and type 6, respectively. The surface morphologies of different types of wafers were measured by atomic force microscopy (AFM) in a tapping mode (Veeco Dimension Icon). The wafers were cut into pieces of samples each with a size of 10 mm×10 mm for electrical investigation. The four 1 mm×1 mm Ti electrodes were deposited on the corners of the square samples by a magnetron sputtering system through a metal mask. Ti film with a purity of $> 99.99\%$ was grown at a pure argon pressure of 1.0 Pa for 15 min at a base pressure of 9×10^{-5} Pa. The thickness of Ti was found to be 40 nm. During deposition, the growth temperature was kept below 100 °C. The contact property was characterized by the current–voltage curve (I–V curve) using a Hall effect measurement system (LakeShore 7704A). The I–V curves were measured between two adjacent electrodes of each sample.

3. Results and discussion

3.1. Surface morphologies of different SiC surfaces

The surface morphologies of different substrates are shown in Fig. 1. In Fig. 1(a), lots of deep scratches

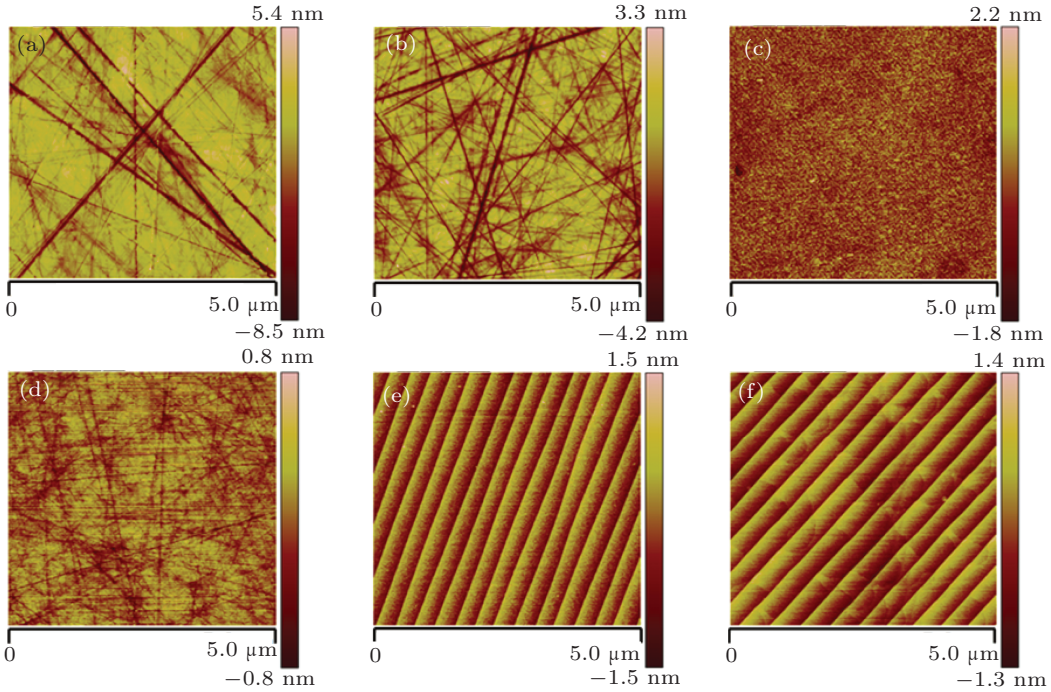


Fig. 1. (colour online) The AFM surface morphologies of SiC substrates with different treatment procedures: (a) sample type 1, (b) sample type 2, (c) sample type 3, (d) sample type 4, (e) sample type 5, (f) sample type 6.

induced by diamond particles in slurry are clearly seen for sample type 1 with an average surface roughness (R_a) of 1.30 nm. Figure 1(b) shows a better surface with shallow scratches for sample type 2 with a R_a of 0.80 nm. In Fig. 1(c), no obvious scratch can be seen on the surface of sample type 3 and the surface roughness is measured to be 0.43 nm. Figure 1(d) shows the surface morphology of sample type 4. Although shallow scratches exist on the surface, a smooth surface roughness of 0.18 nm is observed. For samples type 5 and 6, regular steps are clearly observed after the wafers were thermally treated in H_2 as shown in Figs. 1(e) and 1(f), respectively. The surface roughness is 0.40 nm and the width and height of regular step is 380 nm and 1.5 nm for sample type 5 respectively, while sample type 6 shows a similar morphology with R_a of 0.37 nm and the step width and height of 420 nm and 1.5 nm respectively.

3.2. Current–voltage characteristics of Ti/SiC

The I–V characteristics of Ti contact on different SiC samples are shown in Fig. 2. It can be clearly seen that the I–V curves of sample types 1 and 4 show good Schottky behaviours, while the other curves exhibit good ohmic properties. The mechanisms of Ti/SiC ohmic contact for sample types 2 and 3 are explained as follows. As is well known, the density of surface states on the surface of semiconductor is very high, which results in the Fermi level pinned in the energy gap.[12] The carrier transport is restricted by the barriers induced by these surface states. In general, the ohmic contact property can be obtained by lowering the barrier height.[13] Hydrogenation is suggested to be an effective way to reduce the density of surface states. HF acid solution is often used in the Si (111) surface cleaning process to dissolve the silicon dioxide layer grown on the Si substrate.[14,15] The solution etches the layer quickly and leaves a hydrogen-terminated surface after the etching has been completed. The etched surface keeps stable even after exposuring in air for several hours without oxidation, and the gap states of Si(111) surface are reduced to a very low level, which leads to a low surface recombination and an unpinned surface Fermi level. Trucks *et al.* reported on a theoretical result about H-terminated Si surfaces etched by HF acid based on transition-state calculations using Si compounds.[16] The mechanism proposed to explain the H-terminated Si surface etched by HF acid was based on the polarization of Si–Si bond and the selectivity of HF attachment. Watanabe *et al.*[17] found that an atomic flat surface that was homogeneously covered with silicon monohydride (–SiH) normal to the surface and was free of oxidation, could be formed by HF etching followed by immersion in water. Since both the (0001) Si-face 6H-SiC and the Si (111) surfaces are Si-terminated with (111) crystallographic direction, the monohydride termination is expected to exist on the surface of (0001) Si-face 6H-SiC. Thus, it can be concluded that the ohmic properties of sample types 2 and 3 come from the hydrogenation of (0001) Si-face 6H-SiC surface etched by HF acid solution treatment.

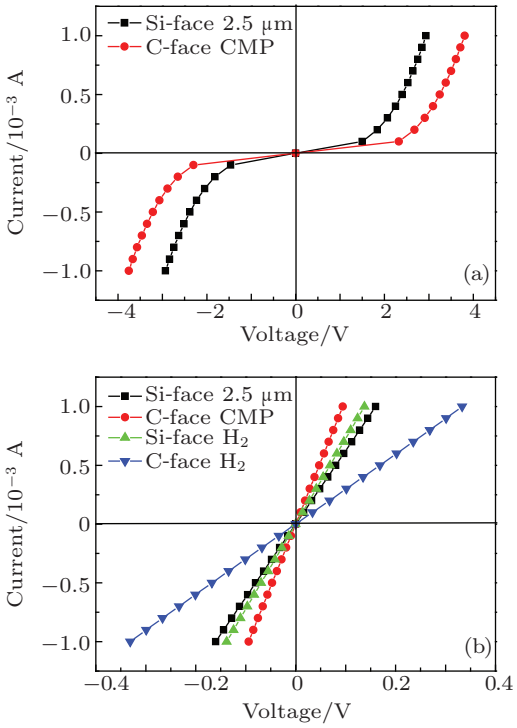


Fig. 2. (colour online) The I-V curves of Ti/SiC contact structure with different surface treatment procedures: (a) sample types 1 and 4, (b) sample types 2, 3, 5, and 6.

For the Si-face samples, it can be seen that the surface roughness has an obvious effect on the ohmic contact properties of Ti/SiC. This is caused by the subsurface damages introduced by polishing.[18] The surface will have more subsurface damages for the rough surface. These damages can introduce additional surface states which result in Fermi level pinning. It is hard to lower the barrier height for this kind of surface by HF treatment when the surface roughness is big enough. As shown by the surface roughness data, the sample type 1 has more serious damages to subsurface than sample type 2, resulting in the quite

different properties of Ti contact on these two samples. Therefore, it can be concluded that when the subsurface damage is serious enough (i.e. $R_a = 1.30$ nm in this paper), the contact property of Ti on (0001) Si-face 6H-SiC will change from the ohmic property to a Schottky property.

Besides the HF acid solution treatment, another effective way to obtain H-terminated surface on (0001) Si-face 6H-SiC is H_2 treatment. Lin *et al.*[19] reported on the treatment of (0001) Si-face 6H-SiC in H_2 plasma which leads to a successful hydrogenation of the surface identified by X-ray photoelectron spectroscopy (XPS) and high energy electron diffraction pattern. van Elsbergen *et al.*[20] obtained (0001) Si-face 6H-SiC by exposing the surfaces at elevated temperatures to atomic hydrogen in an ultrahigh vacuum environment. Tsuchida *et al.*[21] showed direct evidence for a successful surface hydrogenation of SiC by infrared spectroscopy for the first time. H_2 treatment can also remove the pinned surface states. Thus, the lowering of barrier height can be achieved. The Ti ohmic property is observed on this kind of surface (sample type 5 in this paper) as shown in Fig. 2.

For the C-face samples, Ti ohmic contact is obtained only for sample type 6. This is attributed to the formation of H-terminated surface on C-face by H_2 treatment.[22] Although the surface roughness of sample type 4 is much lower than that of sample type 2, the I–V curve of sample type 4 shows typical Schottky behaviour. This is because the HF acid solution does not form the H-terminated surface on C-face, which is different from the Si-face. The reason why the H-terminated surface cannot be formed on the C-face needs further study. The *ab initio* molecular-orbital theory is a useful method to investigate this issue, which has been used by Trucks *et al.*[16] to study the HF etching of Si surface from a point of view of activation barriers to HF attack of the Si surface.

For the H-terminated surface, the surface stability can be a problem. Seyller *et al.*[22] studied the H_2 treated surfaces by XPS and found that the surfaces were still stable after two-day exposure to air. No study on the stability of H-terminated surface etched by HF has been reported. The stability of H-terminated surface against thermal treatment is an interesting issue and needs further study.

4. Conclusions

In the present study, Ti is deposited on n-type Si-face and C-face 6H-SiC with different surface morphologies. The ohmic contact properties of Ti/6H-SiC are studied. It is found that the H-terminated surface is essential for the fabrication of Ti ohmic contact to n-type 6H-SiC without high-temperature anneal. The H-terminated surface on Si-face 6H-SiC can be obtained by both dipping SiC into HF acid solution and thermal heating SiC in H_2 atmosphere, while the formation of H-terminated surface on the C-face 6H-SiC can be obtained only by the thermal heating SiC in H_2 atmosphere.

References

[1] Morkoc H, Strite S, Gao G B, Lin M E, Sverdlov B and Burns M 1994 *J. Appl. Phys.* **76** 1363

[2] Kato T, Miura T, Nagai I, Taniguchi H, Kawashima H, Ozawa T, Arai K and Okumura H 2011 *Mater. Sci. Forum* **679** 3

[3] Thomas B, Hecht C, Stein R and Friedrichs P 2006 *Mater. Sci. Forum* **527** 135

[4] Satoh M, Jinushi T and Nakamura T 2009 *Mater. Sci. Forum* **615** 485

[5] Gao Y, Soloviev S I and Sudarshan T S 2002 *J. Electron. Mater.* **31** 376

[6] Huang W, Chen Z Z, Chen Y, Shi E W, Zhang J Y, Liu Q F and Liu Q 2010 *Acta Phys. Sin.* **59** 3466 (in Chinese)

[7] Crofton J, Mcmullin P G, Williams J R and Bozack M J 1995 *J. Appl. Phys.* **77** 1317

[8] Crofton J, Beyer L, Williams J R, Luckowski E D, Mohney S E and Delucca J M 1997 *Solid State Electron.* **41** 1725

[9] Hara S, Teraji T, Okushi H and Kajimura K 1996 *Appl. Surf. Sci.* **107** 218

[10] Hara S, Teraji T, Okushi H and Kajimura K 1997 *Appl. Surf. Sci.* **117** 394

[11] Ghandi R, Lee H S, Domeij M, Zetterling C M and Ostling M 2009 *Mater. Sci. Forum* **600** 635

[12] Han S Y and Lee J L 2004 *Appl. Phys. Lett.* **84** 538

[13] Teraji T, Hara S, Okushi H and Kajimura K 1997 *Appl. Phys. Lett.* **71** 689

[14] Burrows V A, Chabal Y J, Higashi G S, Raghavachari K and Christman S B 1988 *Appl. Phys. Lett.* **53** 998

[15] Chabal Y J, Higashi G S, Raghavachari K and Burrows V A 1989 *J. Vac. Sci. Technol.* A **7** 2104

[16] Trucks G W, Raghavachari K, Higashi G S and Chabal Y J 1990 *Phys. Rev. Lett.* **65** 504

[17] Watanabe S, Nakayama N and Ito T 1991 *Appl. Phys. Lett.* **59** 1458

[18] Agarwal S and Rao P V 2008 *Int. J. Mach. Tool. Manu.* **48** 698

[19] Lin M E, Strite S, Agarwal A, Salvador A, Zhou G L, Teraguchi N, Rockett A and Morkoc H 1993 *Appl. Phys. Lett.* **62** 702

[20] van Elsbergen V, Janzen O and Monch W 1997 *Mater. Sci. Eng.* B **46** 366

[21] Tsuchida H, Kamata I and Izumi K 1997 *Appl. Phys. Lett.* **70** 3072

[22] Seyller T, Sieber N, Mantel B F, Ristein J, Ley L, Heller T, Batchelor D R and Schmeisser D 2001 *Appl. Phys. Lett.* **78** 1216