Ohmic Contact Properties of Multi-Metal Films on n-Type 4H-SiC*

Han Ru[1,†], Yang Yintang[1], Wang Ping[1], Cui Zhandong[2], and Li Liang[2]

(1 *Key Laboratory of Wide Band-Gap Semiconductor Materials and Devices of the Ministry of Education, Xidian University, Xi'an　710071, China*)

(2 *The 13th Research Institute, CETC, Shijiazhuang　050051, China*)

Abstract: An investigation of Au/Ti/Ni and Au/Ti/Pt ohmic contacts to n-type 4H-SiC and the behavior of metal films on SiC with thermal anneals is reported. Specific contact resistance as low as $2.765\times10^{-6}\Omega\cdot cm^2$ was achieved after rapid thermal annealing in N_2 for 2min at 950℃. SIMS analysis shows that the formation of Ni silicide after annealing supported a number of carbon atoms' outdiffusion from the SiC to form interstitial compound TiC. This process can create abundant C vacancies near the interface. It is the carbon defect layer that enhances the defect-assisted tunneling. The interface band structure within the defect level could make it clear why the metal-SiC contacts become ohmic during annealing.

Key words: silicon carbide; ohmic contact; carbon vacancy; interface band structure
PACC: 7280J; 7340
CLC number: TN30　　**Document code**: A　　**Article ID**: 0253-4177(2007)02-0149-05

1 Introduction

Since every device must be connected in some way to the external world via metallic wire or probe tip, low resistance ohmic contacts are essential to high performance semiconductor devices. This is a well-known fact that makes no exception for SiC devices. For wide band-gap semiconductors, it is difficult to produce low resistance contacts due to the very low value of the metal work function[1,2]. As such, the formation of ohmic contact on highly doped SiC substrate requires an annealing process at high temperatures (700 ~ 1200℃)[3,4]. However, the mechanism by which the metal-SiC contacts become ohmic during annealing is not known. Conventional wisdom considers that at least one of the phases formed (metal silicide or metal carbide) during the contact anneal is responsible for the ohmic behavior[5]. Nikitina[6] reported that positively charged C vacancies may be associated with an increased electron concentration under the contact to promote tunneling in n-type SiC. However the results of Mohammad[7] indicate that the phases formed are not the primary mechanism responsible for the ohmic behavior. Instead, changes in the SiC surface created during the annealing process are responsible for it.

In this paper, we report that for Au/Ti/Ni and Au/Ti/Pt ohmic contacts on 4H-SiC, these structures result in reduced excess carbon at the interface by providing a Ti source for any free C. After measurement of their contact resistivity, secondary ion mass spectrometry (SIMS) was used to study the interdiffusion of each element at the interface. The mechanism involved in ohmic contact formation is proposed by analyzing the results of the experiment.

2 Experiment

Sample 1 is a commercial Cree 4H-SiC wafer. Substrates were n-type as-grown, but had a lightly doped p-type 4H-SiC epilayer ($p = 2.0\times10^{16} cm^{-3}$) with a thickness of 2.0μm. Prior to the formation of low contact resistance ohmic contacts on SiC, a highly doped area is necessary. The substrates were ion implanted with N^+ at 400℃ in order to increase the ionization grade and reduce the

* Project supported by the Program of the Ministry of Education of China (No.02074) and the Pre-Research Foundation from the National Ministries and Commissions (No.41308060105)

† Corresponding author. Email: hr526@tom.com

Received 31 August 2006, revised manuscript received 3 October 2006

©2007 Chinese Institute of Electronics

defects induced in the implantation process. First, a threefold (40,70, and 120keV) implantation was used to form an n-well with a mean concentration of $2.5\times10^{17}cm^{-3}$. Then, for the uniformity dopant distribution in SiC, threefold implantation was carried out to form heavily doped concentration (N concentration: $5.6\times10^{19}cm^{-3}$) for the low resistance ohmic contacts. The doses were activated in pure Ar atmosphere at 1600℃ for 1h. The final activated carrier concentration is $5\times10^{18}cm^{-3}$. After cleaning, micropatterns were formed with photoresist to determine the ohmic contact resistivity using linear transmission line method (L-TLM) structures. Titanium and Ni layers were sequentially deposited on the 4H-SiC substrates in a high vacuum chamber. An Au layer was thermally evaporated to reduce the spreading resistance. This can be written as 'Au/Ti/Ni' contact where the '/' indicates the deposition sequence. The thicknesses of the three layers are Au: 20nm, Ti: 30nm, Ni: 250nm. After lifting off the photoresist, the samples were annealed at 900℃ for 25min in Ar flowing at 2slm.

The other contact was formed on n-type 4H-SiC epitaxial layers with a thickness of 0.25μm and a carrier concentration of $1.0\times10^{19}cm^{-3}$ (sample 2). The main processes to form ohmic contact are the same as above; the difference is the choice of metal and the annealing step. In this sample, Au/Ti/Pt (the thickness is 400/40/20nm) were used as the multi-metal deposited on n-type 4H-SiC, and 2min annealing was performed at 950℃ in N_2 flowing at 8sccm.

3 Results and discussions

3.1 Specific contact resistance

Specific contact resistance (ρ_c) values were measured by the L-TLM model, where the linear electrode patterns with different gap spacing (d) were used. Figure 1 shows the total resistance (R_T) values plotted as a function of the contacts gap spacing for samples 1 and 2.

The specific contact resistance ρ_c can be found using the equation $\rho_c = R_c L_T Z$, where R_C is the contact resistance and L_T is the transfer length, which can be obtained in a R_T versus d plot from the intercept with the vertical axis = $2R_C$ and the intercept with the horizontal axis =

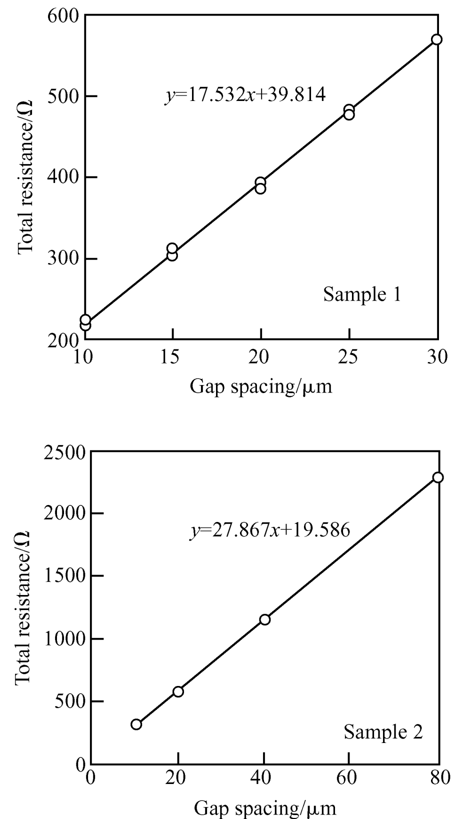

Fig. 1 Plot of total resistance as a function of contact spacing d

$2L_T$. Z is the width of the contact pad. The average ρ_c of sample 1 and sample 2 are $1.912\times10^{-5}\ \Omega\cdot cm^2$ and $2.765\times10^{-6}\ \Omega\cdot cm^2$, respectively. The larger carrier concentration of sample 2 improves the specific contact resistance by one order of magnitude as compared to sample 1.

3.2 SIMS analysis

The SIMS depth analysis of sample 1 reveals evidence for the expected interaction in ohmic contacts between Ti, Ni and the semiconductor, as shown in Fig. 2 (the y-axis is the intensity of the signal; the x-axis is time). At the beginning of onset, the intensities of Au, Ti, and Ni must be strong enough. For the emphasis on interaction in ohmic contacts, the multi-metal signal is not presented here. Ten minutes later, when the electron emission began to attack the ohmic contacts interface, the intensity of each element was recorded. The existence of an Ni signal inside SiC, and the decrease of the Si signal proved that at high annealing temperature most of the Ni film was transformed to the nickel silicide phase. It is speculated

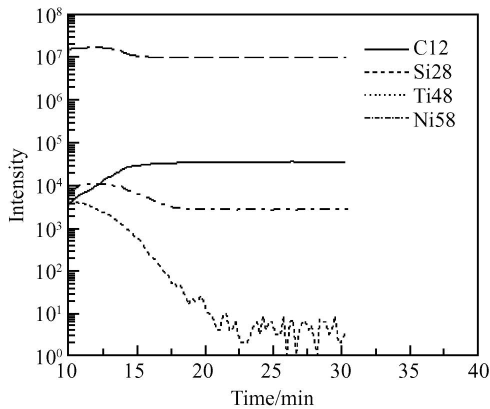

Fig.2　Depth profiles of Ti, Ni, C and Si atoms for Ti/Ni contact on n-type 4H-SiC using secondary ion mass spectrometry (SIMS)

that this was caused by the increased (i.e. metastable) energy state of the sputter-damaged SiC surface. This reaction could produce nickel crystalline voids within the Ni layer, which causes the migration of Ti towards the contact interface. In addition, an abundance of C atoms, leaving at the interface with the silicidation process, outdiffused in the opposite direction of the Ti. When the two atoms collide at high temperature, they must react to form interstitial compound TiC. Because the atomic radius of C is smaller than that of Ti and Ni, the diffusion of C could directly traverse the metal layer but have no use for voids (this could create large numbers of C vacancies at the interface). Therefore outdiffusion of C is faster than indiffusion of Ti. Ti-C reaction must take place on the Ti layer and this process could reduce excess carbon at the interface. Because of the high melting point (3080℃) and the good thermal stability, the TiC layer guarantees high temperature characteristics of the ohmic contact. The formation mechanism of sample 2 is the same as sample 1. Because of the higher carrier concentration and the larger atom radius of Pt, the specific contact resistance of sample 2 is smaller than sample 1. Figures 3 and 4 shows the surface states of samples 1 and 2 obtained for as-deposited and 950℃ anneal, respectively. The accidented surface indicates, similarly, the reaction between the metal layer and SiC. The concave must be brought by reaction between metal films and SiC (formations are Ni silicide and TiC), and the convexity could be a graphite intercalation compound (GIC) formed by a new mechanism[8]. The formation of GIC should be analyzed with some other analysis instruments in the future.

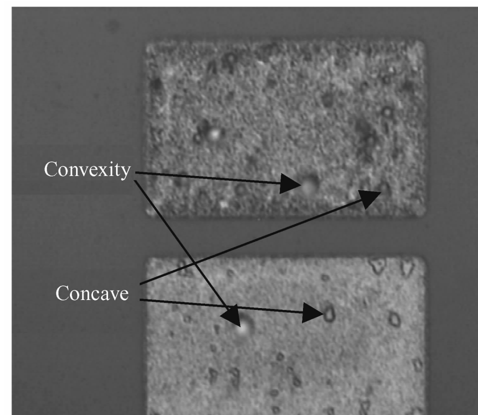

Fig.3　Surface state of sample 1 for 900℃ anneal

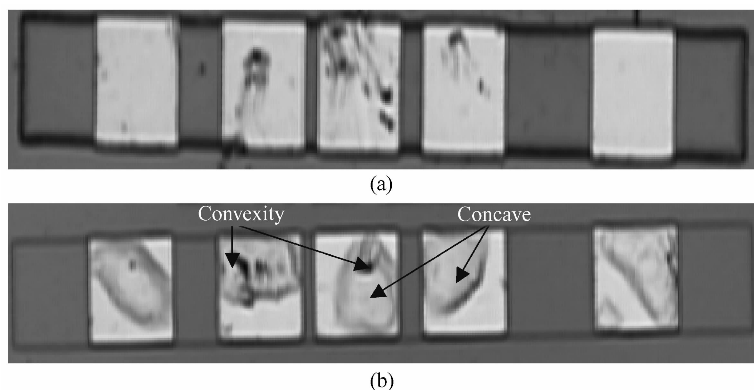

Fig.4　Surface state of sample 2 obtained for as-deposited (a) and 950℃ anneal (b)

3.3　Discussion of barrier height and the interface band structure

Based on the available evidence, the Ni silicide alloy behaves as a semiconductor with an electron affinity close to 4.9eV. The ionization energy level of V_C, which plays a role as a defect

layer, is located at 0.5eV, under the bottom of the conduction band[9]. Therefore, an interfacial layer of Ni silicide and a V_C layer would then lower the barrier height to ~0.4eV, which agrees well with 0.35eV reported by Nakamura[10]. For sample 1, when $\rho_c = 1.912 \times 10^{-5} \Omega \cdot cm^2$ and the Richardson constant $A^* = 146A/(cm^2 \cdot K^2)$ were substituted into $\rho_c = (k/qA^* T)\exp(q\Phi_{Bn}/kT)$, the barrier height Φ_{Bn} was calculated to be 0.315eV. This drop of Φ_{Bn} should be associated with enhanced C vacancies because of the presence of the Ti layer.

To clarify the mechanism for the formation of ohmic contacts, a basic model of interface band structure is summarized in Fig. 5. It is believed that the interface between the as-deposited metal and the silicon carbide is similar to the one shown in Fig. 5(a). Considering the SIMS results mentioned above, both silicidation reaction and out-diffusion of C could produce vacancies, either Si vacancies (V_{Si} act as acceptors) or C vacancies (V_C act as donors), under the Ni silicides. The ohmic contact behavior of the annealed Au/Ti/Ni contacts on n-type SiC is attributed to the V_C defect formation at and near the SiC surface. Such defects can either narrow the depletion width and increase the probability of tunneling (the outdiffusion of C break Si—C bond and bring many vacancies, which predicate the depressed energy band) as illustrated in Fig. 5(b), or decrease the effective barrier height as illustrated in Fig. 5(c). For the existence of the defect layer, there are indirect tunnel processes that can occur, such as a tunnel hopping process. Such processes modify the transparency of the barrier quite markedly from that corresponding to a direct transition. The contact resistance measured using a TLM pattern for the NiSi contact on SiC decreased with up to 150h of annealing at 600℃ and increased for longer annealing times[5]. Similar results have been reported for TaC by Jang (an optimum annealing time of 200h at 1000℃ was observed) and for platinum by Okojie[11] (optimum annealing time of 100h at 600℃ was observed). These results support this defect model (i.e., the defects out-diffuse by excessive annealing and the metal-SiC interface moves from the state shown in Figs. 5(b) and 5(c) to that in Fig. 5(a)). Modification of interface structure and liberation of the barrier height can cause the *I-V* characteristics to change from rectifying to ohmic. A number of carbon vacancies play a key role in forming an ohmic contact through the reduction of effective Schottky barrier height for the transport of electrons.

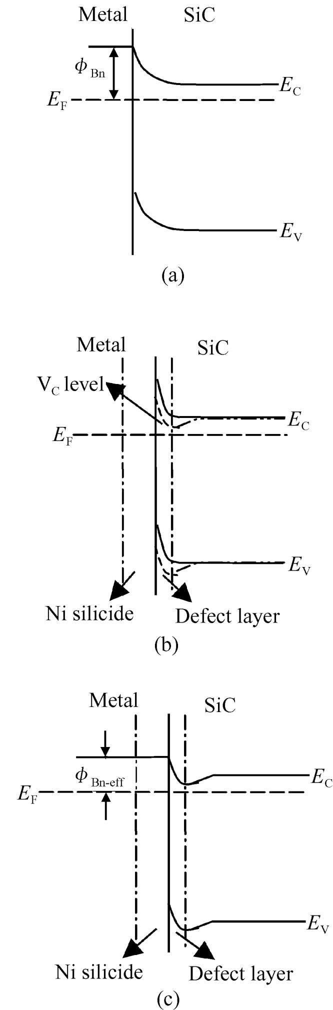

Fig. 5 Interface band diagrams of Ti/Ni on SiC (a) As-deposited Ti/Ni on SiC; (b) C defects, which are created via the outdiffusion of C, reduce the depletion width and increase the tunneling current; (c) Electrically active defects created as in (b) decrease the effective barrier

Thus, if the metal is changed to Re or PtSi (work function of 4.8 and 4.94eV, respectively), the electrons must surmount a ~0.37eV barrier to enter the SiC layer, a negligible difference. Hence, assuming an intimate contact at the metal-SiC interface and that no unusual metal-Si interactions alter the defect density, changing the metal should have a relatively small effect on the current injecting capability of an n^+ contact.

4 Conclusion

In this study, we have reported Au/Ti/Ni and Au/Ti/Pt ohmic contacts to n-type 4H-SiC. After rapid thermal annealing in N_2 for 2min at 950℃, the best specific contact resistance (ρ_c of $2.765\times10^{-6}\Omega\cdot cm^2$) was achieved. The barrier height Φ_{Bn} was calculated to be 0.315eV for Au/Ti/Ni contact. Depth profiles using SIMS indicate the reaction between metal films and SiC. With the outdiffusion of C atoms from SiC, a number of C vacancies must be created to form a carbon defect layer underneath the contacts. This defect layer is very helpful for the formation of ohmic contacts by decreasing the effective barrier height. The real mechanism that causes the *I-V* characteristics to change from rectifying to ohmic can be explained well by the interface band structure within the defect level.

References

[1] Mohammad F A, Cao Y, Chang K C, et al. Comparison of Pt-based ohmic contacts with Ti-Al ohmic contacts for p-type SiC. Jpn J Appl Phys, Part 1: Regular Pages and Short Notes and Review Papers, 2005, 44: 5933

[2] Cao Y, Nyborg L, Jelvestam U, et al. Effect of pre-treatment and nickel layer thickness on nickel silicide/silicon carbide contact. Appl Surf Sci, 2005, 241: 392

[3] Calcagno L, Roccaforte F, La V F. Effects of annealing temperature on the degree of inhomogeneity of nickel-silicide/SiC Schottky barrier. J Appl Phys, 2005, 98: 023713

[4] Blackwood I P, Teng K S, Maffeis T G G, et al. Investigation of annealing effects on the adsorption of Ni on 4H-SiC (0001) surfaces using scanning tunneling microscopy and spectroscopy. J Appl Phys, 2005, 98: 103528

[5] Deeb C, Heuer A H. A low-temperature route to thermodynamically stable ohmic contacts to n-type 6H-SiC. Appl Phys Lett, 2004, 84: 1117

[6] Nikitina I P, Vassilevski K V, Wright N G, et al. Formation and role of graphite and nickel silicide in nickel based ohmic contacts to n-type silicon carbide. J Appl Phys, 2005, 97: 083709

[7] Mohammad F A, Cao Y, Porter L M. Ohmic contacts to silicon carbide determined by changes in the surface. Appl Phys Lett, 2005, 87: 161908

[8] Robbie K, Jemander S T, Lin N. Formation of Ni-graphite intercalation compounds on SiC. Phys Rev B, 2001, 64: 155401

[9] Sang Y H, Ki H K, Jong K K. Ohmic contact formation mechanism of Ni on n-type 4H-SiC. Appl Phys Lett, 2001, 79: 1816

[10] Nakamura T. Schottky barrier height of a new ohmic contact $NiSi_2$ ohmic contacts on n-type 6H-SiC. Solid-State Electron, 2002, 46: 2063

[11] Okojie R S, Spry D, Krotine J. Stable Ti/$TaSi_2$/Pt ohmic contacts on n-type 6H-SiC epilayer at 600℃ in air. Materials Reasearch Society Symposium Proceedings, 2000, 622: 1

多层金属-n型4H-SiC的欧姆接触*

韩　茹[1,†]　杨银堂[1]　王　平[1]　崔占东[2]　李　亮[2]

(1 西安电子科技大学宽禁带半导体材料与器件教育部重点实验室，西安　710071)

(2 中国电子科技集团公司第13研究所，石家庄　050051)

摘要： 研究了热退火条件下Au/Ti/Ni-4H-SiC欧姆接触形成机制.通过950℃下的快速热退火形成的最低欧姆接触电阻为$2.765\times10^{-6}\Omega\cdot cm^2$.SIMS分析表明退火过程中NiSi化合物的形成会带来SiC内部多余C原子的溢出，并在接触面上与Ti形成间隙化合物TiC.这一过程造成接触表面存在由大量C空位形成的缺陷层从而增强了表面间接隧穿.通过界面能带结构图直观地解释了欧姆接触在热退火条件下的形成机制.

关键词： 碳化硅；欧姆接触；碳空位；界面能带结构

PACC： 7280J；7340

中图分类号： TN30　**文献标识码：** A　**文章编号：** 0253-4177(2007)02-0149-05

* 教育部重点科技项目(批准号:02074)和国家部委预研计划(批准号:41308060105)资助项目

† 通信作者.Email:hr526@tom.com

2006-08-31收到，2006-10-03定稿

©2007 中国电子学会