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A critical review of theory and progress in Ohmic contacts to p-type SiC

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ABSTRACT

Silicon carbide (SiC) is a promising candidate in high-temperature, high-frequency and high-power applications due to its outstanding properties such as wide band gap, high critical electric field and high thermal conductivity. However, its applications are still limited by the formation of Ohmic contacts to SiC, especially for *p*-type materials. To date, the specific contact resistance of metal contacts to very highly doped *p*-type SiC could reach the order of $10^{-5} - 10^{-6}$ $\Omega \cdot cm^2$after an extremely high temperature annealing process. However, the obtained Ohmic contacts exhibit poor reproducibility and stability. In addition, the formation mechanism of *p*-type SiC Ohmic contact is still unclear. In this paper, based on the formation principle and barrier theory, we present a review of recent progress in Ohmic contacts to *p*-type SiC reported in literature. Emphasis is placed on the formation mechanism of *p*-type SiC Ohmic contact along with future perspectives for research approaches.

1. Introduction

SiC is an attractive semiconductor for high-power, high-frequency, and high-temperature electronic applications due to the excellent material properties such as wide band gap, high critical breakdown electric field, high thermal conductivity and good chemical stability [1,2]. In recent years, SiC Schottky barrier diodes (SBDs), metal-oxidesemiconductor field-effect transistors (MOSFETs), gate turn-off thyristors (GTOs), bipolar junction transistors (BJTS), insulated gate bipolar transistors (IGBTs) etc. have been applied to some extent [1–4]. However, the advantages of SiC material properties are still not fully realized in the performance of SiC devices. There are still some challenging aspects hindering the achievement of SiC devices operating at the theoretical limits. The performance and reliability of SiC devices need to be further improved [5–13].

One of the main technological problems to develop high-performance SiC-based devices is the effective control of metal/SiC contact properties to fabricate low resistivity and high stability SiC Ohmic contact. Until now, the fabrication and formation mechanism of Ohmic contacts to *n*-type SiC have been systematically studied [5–11]. However, it is still a great challenge to overcome in preparation of low-resistance and high-stability Ohmic contacts to *p*-type SiC due to the large work function, low hole mobility, and dopant activation percentage for *p*-type materials. In this paper, the recent progress in Ohmic contacts to *p*-type SiC have been reviewed including the current conduction, barrier theory, electrical properties, especially the formation mechanism of *p*-type SiC Ohmic contacts along with the possible future research directions.

2. Principle of Ohmic contact to p-type SiC

An Ohmic contact is defined as having a linear symmetric current-voltage (*I-V*) relationship and negligible resistance between metal and semiconductor as compared with the bulk resistance of a device. Theoretically, the electrical properties of metal contacts to semiconductor are determined by the height and thickness of Schottky barrier at the interface. In particular, as low and/or narrow barrier as possible for Ohmic contact are required.

It is well known that the carrier transportation mechanism at the interface between metal and SiC can be explained by the thermionic emission (TE) model, field emission (FE) model, or thermionic field emission (TFE) model which is a combination of TE and FE [14]. The relative contribution of these components depends on both temperature and doping level which is related to the Padovani-Stratton parameter $E_{00} = q\hbar/2\sqrt{(N_A/m * \varepsilon)}$, where N_A is the acceptor concentration, $\hbar$ is the reduced Plank constant, $m*$ is the effective mass of electron and ε is the dielectric permittivity of 4H-SiC. The ratio E_{00}/KT gives an indication of the relative importance of TE ($E_{00}/KT < 0.5$), FE ($E_{00}/KT > 5$) or TFE ($0.5 < E_{00}/KT < 5$).

For low doping level, $E_{00}/KT > 5$, electrons emit from the semiconductor over the potential barrier into the metal. The standard TE is used to obtain the specific contact resistance (ρ_c), which is defined as the derivative of the voltage (V) with respect to the current density (J) across the interface when evaluated at zero bias$(\partial V/\partial J)_{V=0}$.

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$$\rho_c = \left(\frac{\partial V}{\partial J}\right)_{V=0} = \left(\frac{k}{qA^*T}\right)\exp\left(\frac{\Phi_{Bp}}{kT}\right) \propto \exp\left(\frac{\Phi_{Bp}}{kT}\right) \quad (1)$$

where A^* is the effective Richardson constant (for 4H-SiC, A^* is 146 $\mathrm{Acm^{-2}K^{-2}}$). $\rho_c$decreases exponentially as the barrier height (Φ_{Bp}) decreases. Low Φ_{Bp} should be used to obtain small ρ_c.

For a very high doping concentration, $E_{00}/KT > 5$, quantum-mechanical tunneling of electrons through the barrier occurs. FE mechanism plays a dominant role. In this case, ρ_c exponentially decreases with the increase of the square root of the carrier concentration (N_A), which is given by

$$\rho_c = \left(\frac{\partial V}{\partial J}\right)_{V=0} \propto \exp\left(\frac{\Phi_{Bp}}{\sqrt{N_A}}\right) \quad (2)$$

For a relatively high doping level, $0.5 < E_{00}/KT < 5$, tunneling occurs at an energy where the product of carrier density and tunneling probability is at a maximum. TFE is the dominant carrier transport mechanism. ρ_c is dependent on Φ_{Bp}, $N_A$and T, which is represented as

$$\rho_c = \left(\frac{\partial V}{\partial J}\right)_{V=0} \propto \exp\left(\frac{\Phi_{Bp}}{\sqrt{N_A}\coth\left(\frac{E_{00}}{kT}\right)}\right) \quad (3)$$

It is concluded that ρ_c is dependent on Φ_{Bp} (in all mechanisms), N_A (in TFE and FE), and T (more sensitive in TE and TFE). Fig. 1 shows the relationship between E_{00}/KT and N_A for p-type 4H-SiC. Theoretical calculations can predict which mechanism plays the dominant role in carrier transport. I. when $N_A < 9.4 \times 10^{17}\,\mathrm{cm}^{-3}$, TE dominates the carrier transport process. II. when $N_A > 9.4 \times 10^{19}\,\mathrm{cm}^{-3}$, FE is dominant. III. when $9.4 \times 10^{17}\,\mathrm{cm}^{-3} < N_A < 9.4 \times 10^{19}\,\mathrm{cm}^{-3}$, TFE is the dominant carrier transport mechanism.

When N_A is relatively high, barrier lowering mechanism such as band narrowing, image force and tunneling effect should be considered. Reduction of barrier caused by band narrowing ($\Delta\Phi_{BGN}$) is given by [15]:

$$\Delta\Phi_{BGN} = A_{pv}\left(\frac{N_A}{10^{18}}\right)^{1/3} + B_{pv}\left(\frac{N_A}{10^{18}}\right)^{1/2} \quad (4)$$

where A_{pv} and B_{pv} [16] are 1.3×10^{-2} and 1.15×10^{-3} for 4H-SiC, respectively.

Image force reduction ($\Delta\Phi_{IFL}$) is represented as [17]

$$\Delta\Phi_{IFL} = \left[\frac{q^3N_A}{8\pi^2\varepsilon^3}\left(V_d - \frac{kT}{q}\right)\right]^{1/4} \quad (5)$$

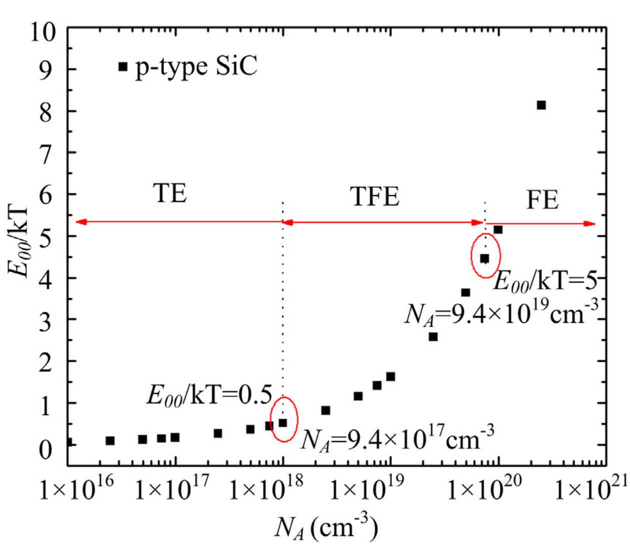

Fig. 1. E_{00}/KT as a function of N_A for p-type 4H-SiC.

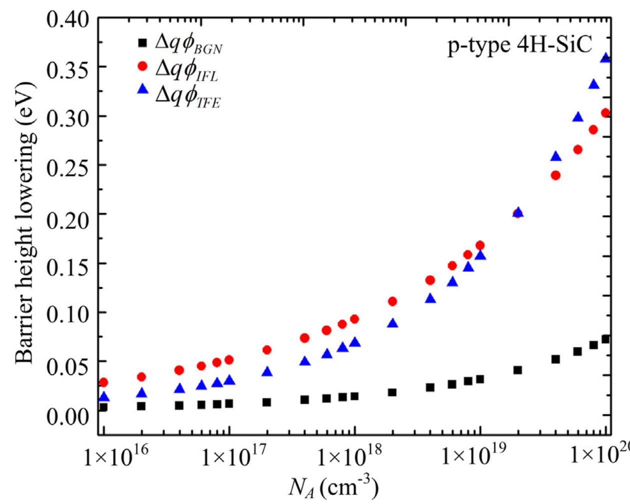

Fig. 2. (Color online) Calculated barrier height lowering as a function of N_A.

$$V_d = \Phi_{Bp} - V - \Phi_p \quad (6)$$

where V_d is the voltage drop on depletion layer and Φ_p is the Energy difference between the valence band maximum and Fermi level.

The barrier lowering by tunneling effect ($\Delta\Phi_{TFE}$) is expressed as [18]

$$\Delta\Phi_{TFE} = (3/2)^{2/3}(E_{00})^{2/3}(V_d)^{1/3} \quad (7)$$

Fig. 2 shows the calculated barrier height lowering ($\Delta\Phi$) as a function of N_A when the value of Φ_{Bp} is 1.0 eV with a zero-bias. It can be seen that $\Delta\Phi$ is increased with the increase of N_A. $\Delta\Phi_{TFE}$ increases most rapidly with increase in N_A.

3. Barrier theory of Ohmic contact to p-type SiC

From Eqs. (1)–(3), Φ_{Bp} should be as low as possible to achieve good Ohmic contact in all three carrier transport mechanisms. According to Schottky-Mott model [19–20], Φ_{Bp} is ideally determined by the metal work function (Φ_m).

$$\Phi_{Bp} = (E_g + \chi) - \Phi_m \quad (8)$$

where$\chi$is the electron affinity of SiC. In theory, the fabrication of low resistance contacts on semiconductors is based on selecting a metal with a high Φ_m for p-type semiconductors to form a low Φ_{Bp}. However, the value of $E_g + \chi$ can reach 7 eV for p-type SiC, while the work functions of almost all metals are in the range of 4.5 eV–6 eV.

In fact, Schottky-Mott theory is little practice for SiC. Φ_{Bp} is often found to be independent of Φ_m. Bardeen [21] proposed a theory to explain this independence. If the density of localized surface states is sufficiently high, the Fermi level in the semiconductor is pinned at the charge neutrality level (Φ_0) in the band gap

$$\Phi_{Bp} = \Phi_0 \quad (9)$$

Based on Bardeen model, Cowley et al. [22] derived the general linear relationship between barrier height and Φ_m for n-type semiconductor. For p-type material, Φ_{Bp} can be derived approximately as

$$\Phi_{Bp} = -S(\Phi_m - \chi) - (1 - S)(E_g - \Phi_0) + E_g \quad (10)$$

where the pinning factor S is related to the density of interface states (D_{it}). S ranges from 0 to 1. When D_{it} is very small, $S \to 1$, the barrier height is consistent with ideal Schottky-Mott model ($\Phi_{Bp} = (E_g + \chi) - \Phi_m$) with a “free-pinned” Fermi level at the interface. When D_{it} is sufficiently high, $S \to 0$, Φ_{Bp} is independent of Φ_m. This situation represents the strongest Fermi level pinning called Bardeen model ($\Phi_{Bp} = \Phi_0$). Therefore, in order to lower Φ_{Bp} to reduce the contact resistivity, effective surface treatments prior to SiC metallization to

Table 1
Ohmic contacts to *p*-type SiC. The deposition and annealing conditions, calculated ρ_c, and SiC information are listed for most of the contact metallizations.

Metallization Stack	Type	Doping Level ($\times 10^{18}\,cm^{-3}$)	Temperature (°C)	Atmosphere	ρ_c ($\times 10^{-5}\,\Omega\cdot cm^{-2}$)	Refs
Ni/Ti/Al/Ni	4H	30	800	Ar	1.5	[89]
Al/Ti/Al	4H	10	1050	N.R.	0.5	[53]
Ni/Al/Ti	4H	100	1000	vacuum	0.3 ± 0.1	[57]
Ni/Ti/Al	4H	4.5	800	vacuum	7	[50]
Ti/Al	4H	4.5	1000	vacuum	2	[50]
Ti/Al	4H	20	900	N_2	6.59	[58]
Ti/Ni	4H	10	1000	Ar	4.1	[92]
Al/Ti	6H	45	1000	Ar	50 ± 40	[56]
Al/Ti	6H	10	1000	vacuum	4.9	[49]
Ti/Al/W	4H	20	1100	N.R.	60	[99]
Ni	4H	20	1000	N.R.	100	[99]
Ge/Ti/Al	4H	4.5	600	vacuum	10	[63]
Ti/Al/Au	4H	10	1050	N_2	6.4	[40]
Al/Ti/Au	4H	30	1000	1% H_2/Ar	1.21	[91]
Ti/NiAl/Au	4H	> 100	600	vacuum	~50	[52]
Ti/NiAl/Au	4H	> 100	650	Ar	18	[95]
Pd/Ti/Pd/Au	4H	30–50	900	1% H_2/Ar	2.8	[102]
Pd/Au	4H	30–50	850	Ar	4.19	[97]
TiN	6H	10	N.R.	N.R.	4.4	[85]
TiC	4H	20	500	10% H_2/Ar	2	[43]
TiC	4H	> 100	950	10% H_2/Ar	1.87 (measured at 300 °C)	[93]
Ti	4H	> 100	700	10% H_2/Ar	27.5 (measured at 300 °C)	[93]
Ti /Si/Co	4H	3.9	850	vacuum	40	[106]
Ti/Al/Si	4H	24	1020	Ar	17	[87]
Al/Si/Ti	4H	30–50	950	Ar	9.6	[88]
Si/Pt	4H	10	1100	vacuum	~4.4	[51]
Pt	4H	10	1100	vacuum	~15	[51]
Pt/Ti	4H	250	1000	vacuum	7 ± 0.27	[84]
Pt/Ti (80:20 at. %)	4H	200	1100	vacuum	74	[101]
Al	4H	4.8	1000	vacuum	42	[33]
Ni(13)/Si(12)/Ni(13)/Si(12)	4H	4.2	960	vacuum	4	[82]
Pd	4H	4	600	N.R.	40	[83]
Ni/Pt/Ti/Al	4H	6–8	1000	vacuum	9	[48]
W/Ni	4H	300	1150	Ar	0.73 ± 0.09	[94]
Ni/W/Ni	4H	0.001	1050	N_2	4.54	[86]
W/Al	4H	100	850	Ar	6.8	[98]
Ni/Cr	4H	7.1	900	vacuum	71/9.5 (3/4 times implanting ions)	[90]
Ti/AlNi/W	4H	> 100	900–950	Ar	2–6	[96]
Ni/W/$TaSi_2$/Pt	4H	100	975	N_2	130/12 (measured at 25 °C /500 °C)	[103]
Mo/Al	6H	1	1200	N_2-H_2	4.5	[100]
Ta/Al	6H	1	1100	Ar	10.4	[100]
Ni/Al	4H	> 5	600	N_2	~10	[104]
Co/Al	4H	9	900	vacuum	40	[105]

release the Fermi level pinning are important. However, as discussed above, since no metal has a work function of more than 6 eV, Fermi level unpinning by surface pretreatments may be not necessarily effective to reduce the barrier height for *p*-type SiC.

Besides, according to FE and TFE, heavy doping of the *p*-type SiC near contact region could produce narrow potential barrier. In this case, good Ohmic contact could be achieved since charge carriers can penetrate the barrier by quantum-mechanical tunneling. However, *p*-type doping is still a key technique problem. The preferred acceptor elements are required to be subjected to thermal treatments performed at extreme high temperature up to 1950–2000 °C.

4. Research progress in p-type SiC Ohmic contact

The existing researches on Ohmic contacts to *p*-type SiC mainly focus on the optimization of the fabrication process, including metal material system, annealing condition, doping concentration, etc. The influences of these parameters on the performance and formation mechanism of Ohmic contact were also studied [23–68,82–106] (summarized in Table 1.). As seen in Table 1., it is required to anneal the contacts formed on highly doped (> $10^{19}\,cm^{-3}$) *p*-type SiC at very high temperatures (> 1000 °C) to fabricate good Ohmic contacts. However, heavily *p*-type doping process is extremely difficult and costly. In addition, extreme annealing temperatures may cause stress in device structures and also result in rough contact surface morphology. The Ohmic contacts often demonstrate poor thermal stability. Moreover, there is a considerable variation in ρ_c with lack of reproducibility. The Ohmic contact formation mechanism after annealing at high temperature is still not understood because of the complicated chemical reaction at the interface.

Shier et al. [47] firstly proposed the method to fabricate *p*-type SiC Ohmic contact. They applied melted Cu-Ti and Al-Si eutectic alloys to wet on *p*-type SiC, forming Ohmic contacts. However, the contact metals penetrate into SiC with a very high ρ_c. Over the years, lots of studies have been carried out for Ohmic contacts to *p*-type SiC, and Ti/Al based metallizations have given the best results in terms of contact resistance. In the mostly used Ti/Al-based metal stacks, ρ_c can reach the order of $10^{-5}\,\Omega\cdot cm^2$, sometimes even as low as $10^{-6}\Omega\cdot cm^2$after an annealing process above 1000 °C [48–59]. The annealing temperature could be reduced to 800 °C by trying to add other metals such as Ni/Ti/Al, Au/Ti/Al, Ge/Ti/Al [60–64].

Due to the complex interface reactions during high temperature annealing, conventional Ti/Al-based Ohmic contact to *p*-type SiC demonstrates poor thermal stability owing to the oxidation of Al at elevated temperatures. In addition, the *p*-type SiC Ohmic contact formation mechanism is still very controversial. Two main different explanations for Ohmic contact to *p*-type SiC have been proposed.

I. Carrier concentration increase and surface defect formation: Al

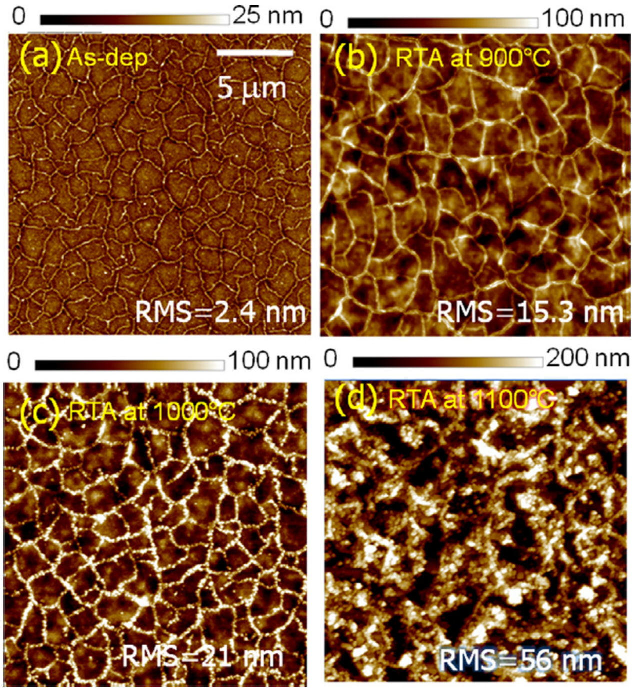

Fig. 3. (Color online) AFM surface morphology acquired for the as-deposited Ti/Al/W contact (a), and for the contacts annealed at 900 °C (b), 1000 °C (c), and 1100 °C (d) (after Ref. 13).

diffuses into the SiC during high temperature annealing, which leads to an increase in the doping concentration at the interface since Al is a *p*-type dopant in SiC. Therefore, the barrier at the interface will be thin enough for charge carriers to tunnel it by TFE and/or FE. In addition, high temperature annealing may also cause surface defects. These localized defect states will cause Fermi level pinning or serve as a capture center, which facilitate carrier to tunnel and hop the barrier that result in the increase of doping concentration and reduction in barrier height, thus improving the performance of Ohmic contacts. Moreover, the changes of surface topography consisting of small pit pits under the contact metal is observed during the annealing process. The electric field may be enhanced by geometric effects at the pit tips when biasing the contact, which will promote the formation of Ohmic contact [12].

Vivona et al. [13] studied the morphological structure of Ti/Al/W contacts to *p*-type implanted 4H-SiC that obtained by Al-ion-implantation. An Ohmic contact with ρ_c of $5.8 \times 10^{-4}\,\Omega\cdot cm^2$was obtained after annealing at 1100 °C in argon atmosphere. The AFM images acquired for the as-deposited and annealed samples are shown in Fig. 3. It indicated that the surface morphology is strongly affected by the thermal annealing. The formation of the Ohmic contact is accompanied with the increase in surface roughness which may cause surface defect, and the interfacial reaction which produces the alloy of $TiAl_3$, $W(SiAl)_2$ and TiC. Also, Transmission electron microscopy (TEM) analysis as shown in Fig. 4 showed that the Al-rich protrusion penetrating the entire stack down to the SiC substrate may play an important role in the formation of Ohmic contacts. M. Gao et al. [30]. proposed that the interface defect states plays an important role in the reduction of barrier height and the formation of Ohmic contacts in 2007. Auger electron spectroscopy (AES) analysis revealed an interface defect states in SiC surface, which may lead to Fermi level pinning and enhance carrier tunneling. This is advantageous for the formation of Ohmic contacts. Yu et al. [31] studied Ohmic contact to *p*-type SiC using Ni/Ti/Al. The doping concentration of SiC was $2.0 \times 10^{19}\,cm^{-3}$. A lowest ρ_c of $1.8 \times 10^{-5}\,\Omega\cdot cm^2$ was obtained when the samples annealed at 800 °C for 2 min in N_2. X-ray diffraction (XRD) analysis revealed that the Ni_2Si and Ti_3SiC_2 compounds formed at the interface control the current transport

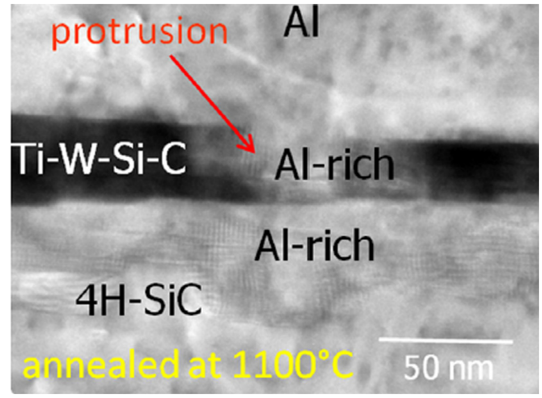

Fig. 4. (Color online) Cross-section TEM image of the interface in the Ti/Al/W contact annealed at 1100 °C. (after Ref. 13).

through the Ni/Ti/Al /SiC interface. The presence of Ni_2Si and Ti_3SiC_2 facilitates the diffusion of Al to the SiC surface, which increases the carrier concentration and promotes the formation of Ohmic contacts. Crofton et al. [32] found that Al-Ti contacts to heavily doped *p*-type SiC exhibits Ohmic properties after annealing at 1000 °C for 2 min. A liquid phase was formed which penetrates into the SiC surface when the ohmic contact was produced. However, it was not established whether the spiking leads to the increase of Al doping. It is nevertheless clear that the spikes are vital to the formation of low ρ_c.

II. Interface alloy formation and intermediate layer barrier adjustment: Al_3Ti, Ti_5Si_3, Ni_2S, Al_4C_3, Al_3C_{4x}, Ti_3SiC_2 and other compounds are produced at the metal/SiC interface during the high temperature annealing process, which promote the formation of *p*-type SiC Ohmic contacts. A lot of studies have shown that the ternary alloy Ti_3SiC_2 which divides the high barrier of metal/SiC contact interface into two low barriers may be correlated with ρ_c lowering. The epitaxial terraced structure of Ti_3SiC_2 with respect to the *p*-type SiC may enhance current conduction across the metal-SiC interface and promotes the formation of Ohmic contacts.

Tsukimoto et al. [33] prepared a low-resistance Ge/Ti/Al Ohmic contact on *p*-type 4H-SiC by low-temperature annealing at 600 °C with a ρ_c of $1 \times 10^{-4}\,\Omega\cdot cm^2$. The Ohmic contact formation could be attributed to the interfacial alloy Ti_3SiC_2 which modulates the barrier at the interface. As shown in Fig. 5, a large Schottky barrier is formed at the interface between Al_3Ti metallic compounds and *p*-type SiC which interrupts the current transport through the contact interface, causing a large contact resistance. However, the formed Ti_3SiC_2 which acts as an intermediate semiconductor layer reduces the barrier height into two low barrier heights. The current can transport through the interface with low barrier heights. Johnson et al. [34] investigated the mechanism of Ohmic behavior of Al/Ti contacts to *p*-type SiC after thermal annealing. It was found that Al diffusion into SiC and electric field enhancement at pit tips play little or no role in the ohmic behavior. The available evidence testified to adjustment of Φ_{Bp} by the formation of the alloys Ti_3SiC_2 and Al_4C_3 as the mechanism of Ohmic contact formation. Konishi et al. [35] studied Ni/Al and Ni/Ti/Al Ohmic contacts on *p*-type 4H-SiC ($N_A = 3.0 - 9.0 \times 10^{18}\,cm^{-3}$) after annealing at 800 °C in an ultra-high vacuum. The obtained ρ_c are $5 \times 10^{-3}\,\Omega\cdot cm^2$and $6.6 \times 10^{-5}\Omega\cdot cm^2$, respectively. Microstructure analysis of the interface indicated that Ni_2Si and $NiAl_3$ were observed at both interfaces. In addition, Ti_3SiC_2 was also observed which may act as an intermediate layer to reduce Φ_{Bp}. Laariedh et al. [36] investigated Ni/Ti/Al/Ni-based Ohmic contacts on *p*-type 4H-SiC. The lowest ρ_c of $1.5 \times 10^{-5}\,\Omega\cdot cm^2$was obtained after annealing at 800 °C for 90 s in argon atmosphere. XRD and secondary ion mass spectrometry (SIMS) indicated that the rapid thermal annealing leads to the formation of Ti_3SiC_2, Ni_2Si, Al_2Ti and $NiAl_3$ intermetallic phases, which adjusts Φ_{Bp} and facilitates the formation of Ohmic contact.

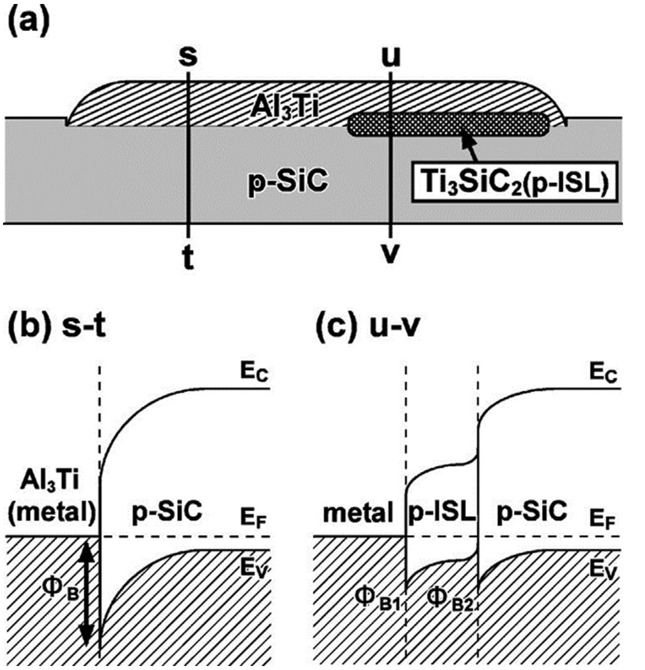

Fig. 5. (Color online) Cross-sectional microstructures of the Ge/Ti/Al contact (a) and the predicted energy-band diagrams at the Al_3Ti/SiC (b) and the Ti_3SiC_2/SiC (c) interfaces (after Ref. 33).

Fisher et al. [37] presented an experimental investigation on Ti/Al-based Ohmic contacts to *p*-type 4H-SiC. With the doping concentration $N_A > 1 \times 10^{19}\,cm^{-3}$, the lowest ρ_c with a mean value of $3.7 \times 10^{-5}\,\Omega\cdot cm^2$was achieved after annealing in argon at 1000 °C for 2 min. The interfacial alloy Ti_3SiC_2 may responsible for the low ρ_c according to the XRD results. Vivona et al. [38] studied electrical and structural properties of Ti/Al/Ni Ohmic contacts to *p*-type implanted 4H-SiC through different techniques. An Ohmic behavior with a ρ_c of $2.3 \times 10^{-4}\,\Omega\cdot cm^2$ can be obtained after 950 °C annealing. The Ohmic contact formation is related to the occurrence of the reaction (Al_3Ni_2 and TiC) and the disorder at the interface. The current transport is dominated by the TE mechanism with a barrier height of 0.56 eV. In 2013, Thierry-Jebali et al. [39] reported the performance of Ohmic contacts fabricated on highly *p*-doped 4H-SiC epitaxial layer selectively grown by vapor-liquid-solid transport. Ohmic behavior can be achieved even without any annealing process. Both 500 °C and 800 °C annealing temperature lead to a minimum value of ρ_c down to$1.3 \times 10^{-6}\,\Omega\cdot cm^2$. The formation of Ohmic contact was attributed to the optimized formation of Ti_3SiC_2 at the metal/SiC interface with a reduction of Φ_{Bp}. Han et al. [40] reported Ti/Al/Au Ohmic contacts with different Ti contents on *p*-type 4H-SiC ($N_A = 1 \times 10^{19}\,cm^{-3}$). It was found that the contact with a higher Ti content (Ti(50 nm)/Al/Au) yields a low ρ_c of $6.4 \times 10^{-5}\,\Omega\cdot cm^2$after annealing at 1050 °C for 3 min. XRD analysis indicated that ternary Ti_3SiC_2 plays an important role in the formation of Ohmic contact. Abi-tannous et al. [41] studied the formation of Ti_3SiC_2-based Ohmic contact on *p*-type 4H-SiC varied the doping concentrations from $1 \times 10^{19}\,cm^{-3}$ to $4 \times 10^{19}\,cm^{-3}$. A low$\rho_c$of $1.1 \times 10^{-4}\,\Omega\cdot cm^2$was obtained after annealing at 1000 °C in vacuum atmosphere with the metal stack of $Ti_{50}Al_{50}$. It was indicated that Ti_3SiC_2 is a key factor for the formation of *p*-type SiC Ohmic contact when the Ti_3SiC_2 directly covers the SiC substrate from TEM measurement. However, the interface alloy Ti_3SiC_2 was not observed to promote the formation of *p*-type SiC Ohmic contact in the report of Buchholt et al. [42]. They grew Ti_3SiC_2 on *n*- and *p*-type 4H-SiC using magnetron sputtering directly. It was found that Ohmic contacts can be achieved for the *n*-type SiC after a high temperature anneal at 950 °C. However, no Ohmic behavior was observed for the contacts to *p*-type SiC.

In addition to the traditional Ti-Al base, other metal stacks such as Ni, TiC, and heavy metal Pt, Au, Au/Pd, etc. have also been studied. Lee et al. [43] reported on the investigation of epitaxial TiC Ohmic contact to Al^+ implanted *p*-type 4H-SiC. The TiC layer was formed by co-evaporation of Ti and C_{60} at low temperatures (< 500 °C). It was found that the lowest ρ_c of $2 \times 10^{-5}\,\Omega\cdot cm^2$after anneal at 500 °C was obtained with a peak Al dopant concentration of $2 \times 10^{19}\,cm^{-3}$. In Ni-based metal stacks, Vang et al. [44] developed Ni/Al based Ohmic contact to p-type 4H-SiC. It was found that ρ_c of Ni/Al contact was decreased with the increase of Al content. A pre-annealing at 400 °C for 1 min effectively reduced the contact resistance by two orders of magnitude.

Heavy metal systems such as Pt, Au, Au/Pd, etc. contacts to heavily doped *p*-type SiC could also form low resistance SiC Ohmic contacts after annealing at high temperatures (> 950 °C). Papanicolaou et al. [45] studied Si/Pt Ohmic contacts to *p*-type 4H-SiC and obtained ρ_c of the order of $10^{-4}\,\Omega\cdot cm^2$after annealing at 1100 °C for 3 min in vacuum. They also investigated Si/Pt/Au and Si/Pt/Ni/Au structures on *p*-type SiC. It was found that Au overlayer could improve the metal conductivity. Jang et al. [46] investigated the properties of Pt and Pt/Si Ohmic contacts to *p*-type 6H-SiC with a concentration (Al doped) of $7.0 \times 10^{18}\,cm^{-3}$. The Ohmic characteristic was observed after annealing at 1100 °C for 5 min in vacuum. The obtained values of ρ_c were $9.1 \times 10^{-3}\,\Omega\cdot cm^2$ and $2.89 \times 10^{-4}\,\Omega\cdot cm^2$, respectively.

In recent years, the process of simultaneously forming Ohmic contacts on *n*-type and *p*-type SiC has attracted extensive attention. Ito et al.[65] successfully obtained Ni/Al Ohmic contacts on *n*-type ($N_D = 1.3 \times 10^{19}\,cm^{-3}$) and *p*-type ($N_A = 7.2 \times 10^{18}\,cm^{-3}$) SiC simultaneously after annealing at 1000 °C for 5 min in an ultra-vacuum environment. The obtained ρ_c were $1.8 \times 10^{-4}\,\Omega\cdot cm^2$and $1.2 \times 10^{-2}\,\Omega\cdot cm^2$ when the Al-layer thickness was in the range of 5 nm to 6 nm for *n*- and *p*-type SiC, respectively. Joo et al. [66] fabricated Ti/Ni bilayer contacts to p^+-type SiC and n^+-type 4H-SiC formed by ion implantation. The results showed that ρ_c of $4.8 \times 10^{-6}\,\Omega\cdot cm^2$ and $1.3 \times 10^{-3}\,\Omega\cdot cm^2$were obtained for n^+ and p^+ type 4H-SiC, respectively. Shimizu et al. [67] investigated the dependence of ρ_c on *n*-type and *p*-type SiC regions on ion species, dose, and implantation temperature. With high-dose ion implantation at room temperature on the *n*-type SiC region, high-dose ion implantation at high temperature on the *p*-type SiC region, low resistance titanium-based Ohmic contacts for SiC MOSFETs with ρ_c of $2.1 \times 10^{-6}\,\Omega\cdot cm^2$ on the *n* region and $1.3 \times 10^{-3}\,\Omega\cdot cm^2$ the *p* region were simultaneously obtained after annealing at 700 °C. In 2018, Zhang et al. [68] studied Pt/$TaSi_2$/Ni/Ti/Ni/SiC simultaneous Ohmic contacts to *n*-type and *p*-type 4H-SiC for the SiC-based devices operating at high temperature and harsh environment. The *n*-type and *p*-type Pt/$TaSi_2$/Ni/Ti/Ni/SiC samples exhibit good Ohmic behaviors with the ρ_c of $3.7 \times 10^{-4}\,\Omega\cdot cm^2$ and $2.9 \times 10^{-3}\,\Omega\cdot cm^2$after annealed at 975 °C for 2 min in N_2, respectively. The Ohmic contacts have good thermal stability. After 300 h aging at 500 °C, just a relatively small increasing of ρ_c($6.5 \times 10^{-4}\,\Omega\cdot cm^2$ and $8.3 \times 10^{-3}\,\Omega\cdot cm^2$ for *n*- and *p*-type samples, respectively) was observed.

5. Conclusion and future perspectives

This paper has summarized and discussed the theory, development, and formation mechanism of Ohmic contacts to *p*-type SiC. Although significant progresses have been made in *p*-type SiC Ohmic contacts, there are still many challenges to overcome. The obtained ρ_c in *p*-type SiC Ohmic contact is generally higher than that in *n*-type SiC and lack of reproducibility and high stability. The formation mechanism of *p*-type SiC Ohmic contact is still not fully understood. To promote the commercialization process of high temperature SiC devices, further investigations on *p*-type SiC Ohmic contacts are necessary. Future works may focus on the following points:

Firstly, barrier theory of metal/*p*-type SiC contact: It is known that the electrical properties of metal contacts to semiconductor are determined by the barrier at the interface. However, the barrier height and thickness are still unable to be controlled effectively. Therefore, the issues of Ohmic contacts to *p*-type SiC are actually those of the contact interface barrier characteristics and underlying mechanism of the current conduction process. In recent years, some researchers have proposed that barrier inhomogeneities in nano scale at metal/SiC interface could affect the current transport process, which may be responsible for the uncontrollable of the barrier height [69–78]. However till now, not enough attention was given in the barrier properties of metal contacts to *p*-type SiC, not to mention the barrier inhomogeneities. Therefore, in order to obtain good Ohmic contacts to *p*-type SiC, it is of great importance to clarify the Schottky barrier and distribution characteristics at metal/*p*-type SiC interface and their effects on the Ohmic properties.

Secondly, adjustment of barrier height: As mentioned above, the *p*-type SiC Ohmic contacts may be benefited from the adjustment of barrier height by the intermediate layer (like Ti_3SiC_2), which has been received extensively attention [33–39]. However, the C cluster at the interface is detrimental to the electrical properties of metal/SiC contact. In order to avoid the effects of C cluster on the Ohmic properties, it is necessary to take a further study on directly intercalation of effective intermediate layer, or schemes of full interface reaction with both C and Si on SiC surface to produce a stable intermediate layer to adjust the barrier height.

Thirdly, mild annealing temperature: Metal/*p*-type SiC mostly needs to be annealed above 1000 °C to obtain an Ohmic contact. However, extreme temperatures may lead to the defects in metal electrodes and interfaces which affect the stability of Ohmic contacts. Some attempts have been made to obtain moderate value of ρ_c which could be obtained after low-temperature or even as deposited through reducing the surface state for both *n*- and *p*-type SiC [5,9,39,43]. Therefore, great effects should be made to achieve good *p*-type SiC Ohmic contact at mild annealing conditions.

Fourthly, secondary Ohmic contacts: When the primary contact has very good Ohmic performance after a high temperature annealing process, the contact metals are then etched off. It is followed by a deposition of a second metal with better thermal and oxidation stability, good adhesion to SiC, etc. The secondary Ohmic contacts can be optimized to improve the reliability of SiC devices for aggressive environments [79–81]. This is a direction need to be concerned.

Finally, simultaneous formation of *n*- and *p*-type Ohmic contacts: For SiC MOSFET devices, simultaneous formation of Ohmic contacts on both *n*- and *p*-type SiC using a single metal system and annealing process will not only simplify device fabrication processes but also miniaturize cell sizes. Recently, some attempts have been made to obtain Ohmic contact performance simultaneously [65–68]. However, it is very hard because of the large difference in barrier height of metal/*n*-type and metal/*p*-type SiC for the same contact metal material. In addition, the mechanisms of simultaneous formation of *n*- and *p*-type SiC Ohmic contacts are not clear.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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References

[1] G. Liu, B.R. Tuttle, S. Dhar, Silicon carbide: a unique platform for metal-oxide-semiconductor physics, Appl. Phys. Rev. 2 (2015) 021307.
[2] Z.M. Cheng, Recent progress in SiC power electronic devices and fabrication process, Chin. J. Semicond. 23 (2002) 673–680.
[3] J. Baligab, Silicon carbide power devices, World Scientific, Singapore, 2006.
[4] K. Sheng, Q. Guo, J. Zhang, Z. Qian, Development and prospect of SiC power devices in power grid, Proc. CSEE 32 (2012) 1–7.
[5] Z. Wang, W. Liu, C. Wang, Recent progress in ohmic contacts to silicon carbide for high-temperature applications, J. Electron. Mater. 45 (2016) 267–284.
[6] P. Leech, A. Holland, G. Reeves, Y. Pan, M. Ridgway, P.T. Anner, Ti/Ni/Au contacts to n-SiC after low energy implantation, Mater. Lett. 166 (2016) 39–42.
[7] S. Liu, Z. He, L. Zheng, B. Liu, F. Zhang, L. Dong, L. Tian, Z. Shen, J. Wang, Y. Huang, Z. Fan, X. Liu, G. Yan, W. Zhao, L. Wang, G. Sun, F. Yang, Y. Zeng, The thermal stability study and improvement of 4H-SiC ohmic contact, Appl. Phys. Lett. 105 (2014) 122106.
[8] M. Xu, X. Hu, Y. Peng, K. Yan, W. Xia, G. Yu, X. Yu, Fabrication of ohmic contact on the carbon-terminated surface of n-type silicon carbide, J. Alloys Compd. 550 (2013) 46–49.
[9] L. Huang, B. Liu, Q. Zhu, S. Chen, M. Gao, F. Qin, D. Wang, Low resistance Ti ohmic contacts to 4H-SiC by reducing barrier heights without high temperature annealing, Appl. Phys. Lett. 100 (2012) 263503.
[10] W. Lu, W.C. Mitchel, G.R. Landis, T.R. Crenshaw, W. EugeneCollins, Ohmic contact properties of Ni/C film on 4H-SiC, Solid-State Electron. 47 (2003) 2001.
[11] S.Y. Han, K.H. Kim, J.K. Kim, H.W. Jang, K.H. Lee, N.-K. Kim, E.D. Kim, J.-L. Lee, Ohmic contact formation mechanism of Ni on n-type 4H-SiC, Appl. Phys. Lett. 79 (2001) 1816.
[12] J. Crofton, L. Beyer, J. Williams, E. Luckowski, S. Mohney, J. DeLucca, Titanium and aluminum-titanium ohmic contacts to p-type SiC, Solid-State Electron. 41 (1997) 1725.
[13] M. Vivona, G. Greco, R. Lo Nigro, C. Bongiorno, F. Roccaforte, Ti/Al/W ohmic contacts to p-type implanted 4H-SiC, J. Appl. Phys. 118 (2015) 035705.
[14] M. Shi, G.Y. Wu, Physics of semiconductor devices, third ed., Xi'an Jiaotong University Press, Xi'an.
[15] S.N. Mohammad, Contact mechanisms and design principles for alloyed ohmic contacts to n-GaN, J. Appl. Phys. 95 (2004) 7940–7953.
[16] U.L. Indefelt, Doping-induced band edge displacements and band gap narrowing in 3C-, 4H-, 6H-SiC, and Si, J. Appl. Phys. 84 (1998) 2628–2637.
[17] M.K. Hudait, S.B. Krupanidgi, Doping dependence of the barrier height and ideality factor of Au/n-GaAs Schottky diodes at low temperatures, Physica B 307 (2001) 125–137.
[18] E.H. Rhoderick, R.H. Williams, Metal-semiconductor contacts, Oxford University Press Clarendon, 1998.
[19] W. Schottky, Halbleitertheorie der Sperrschicht, Naturwissenschaften 26 (1938) 843 843.
[20] N.F. Mott, Note on the contact between a metal and an insulator or semi-conductor, Math Proc Cambridge 34 (1938) 568–572.
[21] J. Bardeen, Surface states and rectification at a metal semi-conductor contact, Phys. Rev. 71 (1947) 717–727.
[22] A.M. Cowley, S.M. Sze, Surface states and barrier height of metal-semiconductor systems, J. Appl. Phys. 36 (1965) 3212–3220.
[23] L. Huang, D. Wang, Barrier inhomogeneities and electronic transport of Pt contacts to relatively highly doped n-type 4H-SiC, J. Appl. Phys. 117 (2015) 204503.
[24] L. Huang, D. Wang, Temperature dependent electrical characteristics of Pt schottky barriers fabricated on lightly and highly doped n-type 4H-SiC, J. Appl. Phys. 54 (2015) 114101.
[25] M. Gülnahar, Temperature dependence of current- and capacitance-voltage characteristics of an Au/4H-SiC schottky diode, Superlattices Microstruct. 76 (2014) 394–412.
[26] Ł. Gelczuk, P. Kamyczek, E. Płaczek-popko, M. Dąbrowska-Szata, Correlation between barrier inhomogeneities of 4H-SiC 1A/600V Schottky rectifiers and deep-level defects revealed by DLTS and laplace DLTS, Solid-State Electron. 99 (2014) 1–6.
[27] L. Huang, F. Qin, S. Li, D. Wang, Effects of surface properties on barrier height and barrier inhomogeneities of platinum contacts to n-type 4H-SiC, Appl. Phys. Lett. 103 (2013) 033520.
[28] S. Shivaraman, L.H. Herman, F. Rana, J. Park, M.G. Spencer, Schottky barrier inhomogeneities at the interface of few layer epitaxial graphene and silicon carbide, Appl. Phys. Lett. 100 (2012) 183112.
[29] Q. Song, Y. Zhang, Y. Zhang, F. Chen, X. Tang, Investigation of current transport parameters of Ti/4H-SiC MPS diode with inhomogeneous barrier, Chinese Phys B. 20 (2011) 057301.
[30] M. Gao, S. Tsukimoto, S.H. Goss, S.P. Tumakha, T. Onishi, M. Murakami, L.J. Brillson, Role of interface layers and localized states in TiAl-based ohmic contacts to p-type 4H-SiC, J. Electron. Mater. 36 (2007) 277–284.
[31] H. Yu, X. Zhang, H. Shen, Y. Tang, Y. Bai, Y. Wu, K. Liu, X. Liu, Thermal stability of Ni/Ti/Al ohmic contacts to p-type 4H-SiC, J. Appl. Phys. 117 (2015) 025703.
[32] J. Crofton, S.E. Mohney, J.R. Williams, T. Isaacs-Smith, Finding the optimum Al-Ti alloy composition for use as an ohmic contact to p-type SiC, Solid-State Electron. 46 (2002) 109–113.
[33] S. Tsukimoto, T. Sakai, M. Murakami, Electrical properties and microstructure of ternary Ge/Ti/Al ohmic contacts to p-type 4H–SiC, J. Appl. Phys. 96 (2004) 4976–4981.
[34] B.J. Johnson, M.A. Capano, Mechanism of ohmic behavior of Al/Ti contacts to p-type 4H-SiC after annealing, J. Appl. Phys. 95 (2004) 5616.
[35] R. Konishi, R. Yasukochi, O. Nakatsuka, Y. Koide, M. Moriyama, M. Murakami, Development of Ni/Al and Ni/Ti/Al ohmic contact materials for p-type 4H-SiC, Mater. Sci. Eng. B 98 (2003) 286–293.
[36] F. Laariedh, M. Lazar, P. Cremillieu, J. Penuelas, J.-L. Leclercq, D. Planson, The role of nickel and titanium in the formation of ohmic contacts on p-type 4H–SiC, Semicond. Sci. Technol. 28 (2013) 045007.
[37] C.A. Fisher, M.R. Jennings, Y.K. Sharma, A. Sanchez-Fuentes, D. Walker, P.M. Gammon, A. Pérez-Tomás, S.M. Thomas, S.E. Burrows, P.A. Mawby, On the

schottky barrier height lowering effect of Ti_3SiC_2 in ohmic contacts to p-type 4H-SiC, Int. J. Fundam. Phys. Sci. 4 (2014) 95–100.

[38] M. Vivona, G. Greco, C. Bongiorno, R. Lo Nigro, S. Scalese, F. Roccaforte, Electrical and structural properties of surfaces and interfaces in Ti/Al/Ni Ohmic contacts to p-type implanted 4H-SiC, Appl. Surf. Sci. 420 (2017) 331–335.

[39] N. Thierry-Jebali, A. Vo-Ha, D. Carole, M. Lazar, G. Ferro, D. Planson, A. Henry, P. Brosselard, Very low specific contact resistance measurements made on a highly p-type doped 4H-SiC layer selectively grown by vapor-liquid-solid transport, Appl. Phys. Lett 102 (2013) 212108.

[40] C. Han, Y. Zhang, Q. Song, Y. Zhang, X. Tang, H. Guo, Interface annealing characterization of Ti/Al/Au ohmic contacts to p-type 4H-SiC, Chin. J. Semicond. 36 (2015) 123006.

[41] T. Abi-tannous, M. Soueidan, G. Ferro, M. Lazar, C. Raynaud, B. Toury, M.-F. Beaufort, J.-F. Barbot, O. Dezellus, D. Planson, A study on the temperature of ohmic contact to p-type SiC based on Ti_3SiC_2 phase, IEEE T Electron Dev. 63 (2016) 2462–2468.

[42] K. Buchholt, R. Ghandi, M. Domeij, C.-M. Zetterling, J. Lu, P. Eklund, L. Hultman, A.L. Spetz, Ohmic contact properties of magnetron sputtered Ti_3SiC_2 on n- and p-type 4H-silicon carbide, Appl. Phys. Lett. 98 (2011) 042108.

[43] S.K. Lee, C.M. Zetterling, E. Danielsson, M. Östling, Electrical characterization of TiC ohmic contacts to aluminum ion implanted 4H-silicon carbide, Appl. Phys. Lett. 77 (2000) 1478–1480.

[44] H. Vang, M. Lazar, P. Brosselard, C. Raynaud, P. Cremillieu, J.-L. Leclercq, J.-M. Bluet, S. Scharnholz, D. Planson, Ni-Al ohmic contact to p-type 4H-SiC, Superlatt. Microstruct. 40 (2006) 626–631.

[45] N.A. Papanicolaou, A. Edwards, M.V. Rao, W.T. Anderson, Si/Pt Ohmic contacts to p-type 4H-SiC, Appl. Phys. Lett. 73 (1998) 2009–2011.

[46] T. Jang, J.W. Erickson, L.M. Porter, Effects of Si interlayer conditions on platinum ohmic contacts for p-type silicon carbide, J. Electron. Mater. 31 (2002) 506–511.

[47] J.S. Shier, Ohmic contacts to silicon carbide, J. Appl. Phys. 41 (1970) 771–773.

[48] K. Vassilevski, K. Zekentes, K. Tsagaraki, G. Constantinidis, I. Nikitina, Phase formation at rapid thermal annealing of Al/Ti/Ni ohmic contacts on 4H-SiC, Mater. Sci. Eng. B 80 (2001) 370–373.

[49] M.R. Jennings, C.A. Fisher, D. Walker, A. Sanchez, A. Pérez-Tomás, D.P. Hamilton, P.M. Gammon, S.E. Burrows, S.M. Thomas, Y. Sharma, F. Li, P.A. Mawby, On the Ti_3SiC_2 metallic phase formation for robust p-type 4H-SiC ohmic contacts, Mater. Sci. Forum 778–780 (2014) 693–696.

[50] S. Tsukimoto, K. Nitta, T. Sakai, M. Moriyama, M. Murakami, Correlation between the electrical properties and the interfacial microstructures of TiAl-based ohmic contacts to p-type 4H-SiC, J. Electron. Mater. 33 (2004) 460–466.

[51] F.A. Mohammad, Y. Cao, K. Chang, L.M. Porter, Comparison of Pt-based ohmic contacts with Ti-Al ohmic contacts for p-Type SiC, Jpn. J. Appl. Phys. Part 1 (44) (2005) 5933–5938.

[52] B.H. Tsao, J. Lawson, Ti/AlNi/W and $Ti/Ni_2Si/W$ ohmic contacts to p-type SiC, J. Scofield Mater. Sci. Forum 527–529 (2006) 903–906.

[53] M.R. Jennings, A. Péreztomás, M. Davies, D. Walker, L. Zhu, P. Losee, W. Huang, S. Balachandran, O.J. Guy, J.A. Covington, T.P. Chow, P.A. Mawby, Analysis of Al/Ti, Al/Ni multiple and triple layer contacts to p-type 4H-SiC, Solid-State Electron. 51 (2007) 797–801.

[54] B.P. Downey, J.R. Flemish, B.Z. Liu, T.E. Clark, S.E. Mohney, Current-Induced degradation of nickel Ohmic contacts to SiC, J. Electron. Mater. 38 (2009) 563–568.

[55] J. Rogowski, A. Kubiak, Investigation of microstructure and chemical composition of Ni contacts to n-type 4H–SiC, Mater. Sci. Eng. B 177 (2012) 1318–1322.

[56] F. Moscatelli, A. Scorzoni, A. Poggi, G.C. Cardinali, R. Nipoti, Al/Ti ohmic contacts to p-type ion-implanted 6H-SiC: mono- and two- dimensional analysis of TLM data, Mater. Sci. Forum 433–436 (2003) 673–676.

[57] P. Fedeli, M. Puzzanghera, F. Moscatelli, R.A. Minamisawa, G. Alfieri, U. Grossner, R. Nipoti, Ni-Al-Ti ohmic contacts on Al implanted 4H-SiC, Mater. Sci. Forum 897 (2017) 391–394.

[58] Y. Tang, H. Shen, X. Zhang, F. Guo, Y. Bai, Z. Peng, X.I. Liu, Effect of annealing on the characteristics of Ti/Al ohmic contacts to p-type 4H-SiC, Mater. Sci. Forum 897 (2017) 395–398.

[59] G. Alfieri, L. Kranz, L. Knoll, V.K. Sundaramoorthy, The effects of illumination on point defects detected in high purity semi-insulating 4H-SiC, Mater. Sci. Forum 924 (2018) 253–256.

[60] L. Kassamakova, R. Kakanakov, N. Nordell, S. Savage, A. Kakanakova-Georgieva, T. Marinova, Study of the electrical, thermal and chemical properties of Pd ohmic contacts to p-type 4H-SiC: dependence on annealing conditions, Mater. Sci. Eng., B 61–62 (1999) 291–295.

[61] S. Tsukimoto, T. Sakai, T. Onishi, K. Ito, M. Murakami, Simultaneous formation of p- and n-type ohmic contacts to 4H-SiC using the ternary Ni/Ti/Al system, J. Electron. Mater. 34 (2005) 1310–1312.

[62] C.M. Eichfeld, M.A. Horsey, S.E. Mohney, A.V. Adedeji, J.R. Williams, Ta-Ru-N diffusion barriers for high-temperature contacts to p-type SiC, Thin Solid Films 485 (2005) 207–211.

[63] T. Sakai, K. Nitta, S. Tsukimoto, M. Moriyama, M. Murakami, Ternary Ti/Al/Ge ohmic contacts for p-type 4H-SiC, J. Appl. Phys. 95 (2004) 2187–2189.

[64] T. Nakamura, M. Satoh, Schottky barrier height of a new ohmic contact $NiSi_2$ to n-type 6H-SiC, Solid-State Electron. 46 (2002) 2063.

[65] K. Ito, T. Onishi, H. Takeda, K. Kohama, S. Tsukimoto, M. Konno, Y. Suzuki, M. Murakami, Simultaneous formation of Ni/Al ohmic contacts to both n- and p-type 4h-sic, J. Electron. Mater. 37 (2008) 1674–1680.

[66] S.J. Joo, S. Baek, S.-C.L. Kim, J.-S. Lee, Simultaneous formation of Ohmic contacts on p^+- and n^+-4H-SiC using a Ti/Ni bilayer, J. Electron. Mater. 42 (2013) 2897–2904.

[67] H. Shimizu, A. Shima, Y. Shimamoto, N. Iwamuro, Ohmic contact on n- and p-type ion-implanted 4H-SiC with low-temperature metallization process for SiC MOSFETS, Jpn. J. Appl. Phys. 56 (2017) 04CR15.

[68] Y. Zhang, T. Guo, X. Tang, J. Yang, Y. He, Y. Zhang, Thermal stability study of n-type and p-type ohmic contacts simultaneously formed on 4H-SiC, J. Alloys Compd. 731 (2018) 1267–1274.

[69] A.V. Kuchuk, V.P. Kladko, A. Piotrowska, R. Ratajczak, R. Jakieła, On the formation of Ni-based ohmic contacts to n-type 4H-SiC, Mater. Sci. Forum 615–617 (2009) 573–576.

[70] R. Pérez, N. Mestres, D. Tournier, P. Godignon, J. Millánb, Ni/Ti ohmic and schottky contacts on 4H-SiC formed with a single thermal treatment, Diamond Relat. Mater. 14 (2015) 1146–1149.

[71] X. He, Z. Chen, L. Li, Effects of sulfur passivation on 6H-SiC (0001) surface and Si/6H-SiC interface, Mater. Sci. Forum 858 (2016) 185–188.

[72] T. Seyller, Passivation of hexagonal SiC surfaces by hydrogen termination, J. Phys.: Condens. Matter 16 (2004) S1755–S1782.

[73] N. Sieber, B.F. Mantel, T. Seyller, J. Ristein, L. Ley, Electronic and chemical passivation of hexagonal 6H-SiC surfaces by hydrogen termination, Appl. Phys. Lett. 78 (2001) 1216–1218.

[74] S.N. Sieber, B.F. Mantel, T. Seyller, J. Ristein, L. Ley, Hydrogenation of 6H-SiC as a surface passivation stable in air, Diamond Relat. Mater. 10 (2001) 1291–1294.

[75] G. Pristavu, G. Brezeanu, M. Badila, R. Pascu, M. Danila, P. Godignon, A model to non-uniform Ni schottky contact on SiC annealed at elevated temperatures, Appl. Phys. Lett. 106 (2015) 261605.

[76] M. Losurdo, G. Bruno, A. Brown, K. Tong-Ho, Study of the temperature-dependent interaction of 4H-SiC and 6H-SiC surfaces with atomic hydrogen, Appl. Phys. Lett. 84 (2004) 4011–4013.

[77] S.J. Schoell, J. Howgate, M. Hoeb, M. Auernhammer, J.A. Garrido, M. Stutzmann, M.S. Brandt, I.D. Sharp, Electrical passivation and chemical functionalization of SiC surfaces by chlorine termination, Appl. Phys. Lett. 98 (2011) 182106.

[78] R. Pérez, N. Mestres, J. Montserrat, D. Tournier, P. Godignon, Barrier inhomogeneities and electrical characteristics of Ni/Ti bilayer Schottky contacts on 4H-SiC after high temperature treatments, Phys. Status Solidi 202 (2005) 692–697.

[79] M.H. Ervin, K.A. Jones, U. Lee, M.C. Wood, Approach to optimizing n-SiC ohmic contacts by replacing the original contacts with a second metal, J. Vac. Sci. Technol., B 24 (2006) 1185–1189.

[80] B. Barda, P. Macháč, S. Cichoň, V. Machovič, M. Kudrnová, A. Michalcová, Origin of ohmic behavior in Ni, Ni2Si and Pd contacts on n-type SiC, J. Siegel Appl. Surf. Sci. 257 (2010) 414–422.

[81] S. Cichoň, P. Macháč, J. Vojtík, NiSi2 and Si secondary ohmic contacts on sic with high thermal stability, Mater. Sci. Forum 740–742 (2013) 797–800.

[82] P. Machácˇ, B. Barda, Improvement of Ni/Si/4H-SiC ohmic contacts by VLS grown sub-contact layer, Microelectron. Eng. 87 (2010) 2499–2503.

[83] E.V. Kalinina, G.F. Kholuyanov, A.V. Shchukarev, N.S. Savkina, A.I. Babanin, M.A. Yagovkina, N.I. Kuznetsov, Pd ohmic contacts to p-SiC 4H, 6H and 15R polytypes, Diamond Relat. Mater. 8 (1999) 1114–1117.

[84] R.S. Okojie, D. Lukco, Simultaneous ohmic contacts to p- and n-type 4H-SiC by phase segregation annealing of co-sputtered Pt-Ti, J. Appl. Phys. 120 (2016) 215301.

[85] A.A. Iliadis, S.N. Andronescu, K. Edinger, J. Orloff, R.D. Vispute, V. Talyansky, R. Sharma, T. Venkatesan, M.C. Wood, K. Jones, Ohmic contacts to p-6H-SiC using focused ion-beam surface-modification and pulsed laser epitaxial TiN deposition, Appl. Phys. Lett. 73 (1998) 3545.

[86] D. Bae, G. Ahn, C. Jeong, K. Kim, Ni/W/Ni ohmic contacts for both n- and p-type 4H-SiC, Electrical Eng. 100 (2018) 2431–2437.

[87] H. Tamaso, S. Yamada, H. Kitabayashi, T. Horii, Ti/Al/Si Ohmic Contacts for Both n-Type and p-Type 4H-SiC, Mater. Sci. Forum 778–780 (2014) 669–672.

[88] R. Kakanakov, L. Kassamakova, I. Kassamakov, K. Zekentes, N. Kuznetsov, Improved Al/Si ohmic contacts to p-type 4H-SiC, Mater. Sci. Eng. B 80 (2001) 374–377.

[89] F. Laariedh, M. Lazar, P. Cremillieu, J.-L. Leclercq, D. Planson, Investigations on Ni-Ti-Al ohmic contacts obtained on p-type 4H-SiC, Mater. Sci. Forum 711 (2012) 169–173.

[90] S.W.Y. Zhang, Y. Zhnag, Y. Zhang, Ohmic contacts of 4H-SiC on ion-implantation layers, Chin. Phy. B 19 (2010) 017204.

[91] L. Kolaklieva, R. Kakanakov, M. Marinova, E. Polychroniadis, Structural analysis of Au/Ti/Al/SiC contacts in dependence on the initial composition and annealing, J. Nano Res.-Sw. 12 (2010) 55–63.

[92] T. Ohyanagi, Y. Onose, A. Watanabe, Ti / Ni bilayer Ohmic contact on 4H-SiC, J. Vac. Sci. Technol. B 26 (2008) 1359.

[93] S.-K. Lee, C.-M. Zetterling, M. Ostling, J.-P. Palmquist, H. Hogberg, U. Jansson, Low resistivity Ohmic titanium carbide contacts to n- and p-type 4H-silicon carbide, Solid-State Electron 44 (2000) 1179–1186.

[94] K.C. Kragh-Buetow, R.S. Okojie, D. Lukco, S.E. Mohney, Characterization of tungsten–nickel simultaneous Ohmic contacts to p- and n-type 4H-SiC, Semicond. Sci. Technol. 30 (2015) 105019.

[95] B.-H. Tsao, J.W. Lawson, J.D. Scofield, J.F. Baca, TEM observations of Ti/AlNi/Au contacts on p-Type 4H-SiC, Mater. Sci. Forum 645–648 (2010) 729–732.

[96] B.-H. Tsao, S. Liu, J. Scofield, Improved AlNi Ohmic contacts to P-Type SiC, Mater. Sci. Forum 457–460 (2004) 841–844.

[97] R. Kakanakov, L. Kassamakova, N. Hristeva, G. Lepoeva, Reliable ohmic contacts to LPE p-type 4H-SiC for high-power p-n diode, Mater. Sci. Forum 389–393 (2002) 917–920.

[98] B.P. Downey, S.E. Mohney, T.E. Clark, J. Flemish, Reliability of aluminum-bearing ohmic contacts to SiC under high current density, Microelectron Reliab. 50 (2010)

1967–1972.
[99] F. Roccaforte, M. Vivona, G. Greco, R.L. Nigro, F. Giannazzo, S.D. Franco, C. Bongiorno, F. Iucolano, A. Frazzetto, S. Rascunà, A. Patti, M. Saggio, Ti/Al-based contacts to p-type SiC and GaN for power device applications, Phys. Status Solidi A 214 (2017) 1600357.
[100] J.O. Olowolafe, J. Liu, R.B. Gregory, Effect of Si or Al interface layers on the properties of Ta and Mo contacts to p-Type SiC, J. Electron. Mater. 29 (2000) 391–397.
[101] R.S. Okojie, D. Lukco, Pt: Ti Diffusion Barrier, Interconnect, and Simultaneous Ohmic Contacts to n- and p-Type 4H-SiC, Mater. Sci. Forum 924 (2017) 381–384.
[102] L. Kolaklieva, R. Kakanakov, E.K. Polychroniadis, E. Pavlidou, I. Tsiaousis, B. Albert, A. Andreadou, Formation and characterization of nanolayered Pd-based metal/p-4H SiC systems with Ohmic behaviour, J Nano Res-Sw 10 (2010) 77–85.
[103] Y. Li, Y. Zhang, X. Tang, T. Guo, Y. Zhang, Extremely thermal Stable Ni/W/$TaSi_2$/Pt simultaneous Ohmic contacts to n-type and p-type 4H-SiC, Mater. Sci. Forum 924 (2018) 401–404.
[104] M. Ekström, S. Hou, H. Elahipanah, A. Salemi, M. Östling, C.-M. Zetterling, Low temperature Ni-Al Ohmic contacts to p-type 4H-SiC using semi-salicide processing, Mater. Sci. Forum 924 (2017) 389–392.
[105] O. Nakatsuka, K. Yasuo, M. Murakami, CoAl Ohmic contact materials with improved surface morphology for p-Type 4H-SiC, Mater. Sci. Forum 389–393 (2002) 885–888.
[106] K.H. Jung, N.I. Cho, J.H. Lee, S.J. Yang, C.K. Kim, B.T. Lee, K.H. Rim, N.K. Kim, E.D. Kim, Titanium-based ohmic contact on p-Type 4H-SiC, Mater. Sci. Forum 389 (2002) 913.