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Improved Ni Based Composite Ohmic Contact to *n*-SiC for High Temperature and High Power Device Applications

by M. W. Cole, P. C. Joshi, C. W. Hubbard, M. C. Wood, M. H. Ervin, B. Geil, and F. Ren

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Abstract

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I. INTRODUCTION

SiC is a promising semiconductor material for high power, high temperature, high frequency, and high radiation tolerance device applications.[1–7] It is the exceptional properties of SiC, such as high breakdown field, large band gap, high thermal conductivity, and large electron saturation velocity, which are responsible for these device application interests.[1–5] It has been reported that most SiC-based electronic devices which cannot sustain a long-term operation at an elevated temperature/power level suffered deterioration of their metal/SiC contacts.[6] Thus, an important concern for realization of SiC devices is the formation of low resistance Ohmic contacts with good thermal, chemical, and mechanical stability. The development of such Ohmic contacts serves to ensure enhanced device reliability under the influence of high power and high temperature in-service operational stress.

To date, many metallizations, namely, Ni, Al/Ni/Al, Cr, Al, Au–Ta, $TaSi_2$, W, Ta, Ti, Ti/Au, $TiSi_2$, Co, Hf, and WSi have been investigated for Ohmic contacts to *n*-SiC.[7,8] As a result of these studies, Ni Ohmic contacts have been suggested as superior candidates due to their reproducible low specific contact resistance, less than $5.0\times 10^{-6}\ \Omega\,cm^2$, and deemed the industry standard Ohmic contact to *n*-SiC.[7,9–11] Fabrication of Ni Ohmic contacts requires a post-deposition anneal at temperatures ranging from 950 to 1000 °C. This anneal causes the Ni to react with SiC to form Ni_2Si and is responsible for achieving Ohmic behavior.[7,9–16] However, the annealing process also causes undesirable features, namely, broadening of the metal–SiC interface, a rough interface morphology heavily laden with Kirkendall voids, carbon segregation at the metal–SiC interface and/or throughout the metal layer, and substantial roughening of the contact surface.[7,10,11,17] Thus, even though Ni contacts possess excellent electrical properties, the above-mentioned features will inhibit long-term reliability and ultimately cause device failure via contact degradation and/or wire bond failure after exposure to extensive high power and high temperature device operational stresses. Therefore, one of the key technology areas which must be addressed and optimized before SiC high power and high temperature devices can be realized is the issue of high performance Ohmic contacts which possess long-term reliability under extreme thermal and electrical operational stress. Optimum contact performance requires strict adherence to a set of fundamental requirements. The most prominent of these requirements include (1) attainment of reproducible low specific contact resistance, (2) a uniform, shallow, and abrupt contact–semiconductor interface with lateral homogeneity of the interfacial phases, and (3) a smooth surface morphology. Additionally, the contact must be temporally, thermally, chemically, and mechanically stable in order to ensure long-term in-service device operational reliability. Thus, the goal of the present investigation was to satisfy the above-mentioned requirements by designing, fabricating, and optimizing an improved Ohmic contact to *n*-SiC for high power and high temperature device applications.

II. EXPERIMENT

The Ni/WSi/Ti/Pt (40 nm:80 nm:25 nm:100 nm) composite metallization was sputter deposited (WSi) and e-beam evaporated (Ni, Ti, Pt) on research grade (0001) 4H *n*-type ($8.0\times 10^{18}\ cm^{-3}$) SiC wafers. Prior to metal deposition the wafers were cleaned in warm electronic grade trichoroethane

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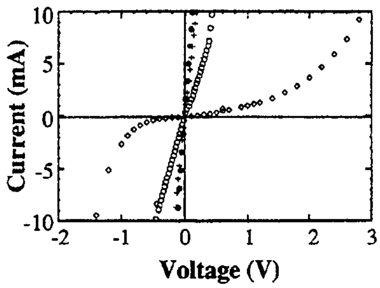

FIG. 1. *I–V* characteristics of the as-deposited (open diamonds), 900 °C (open circles), 950 °C (crosses), and 1000 °C (closed circles) annealed Ni/WSi/Ti/Pt Ohmic contacts to *n*-SiC.

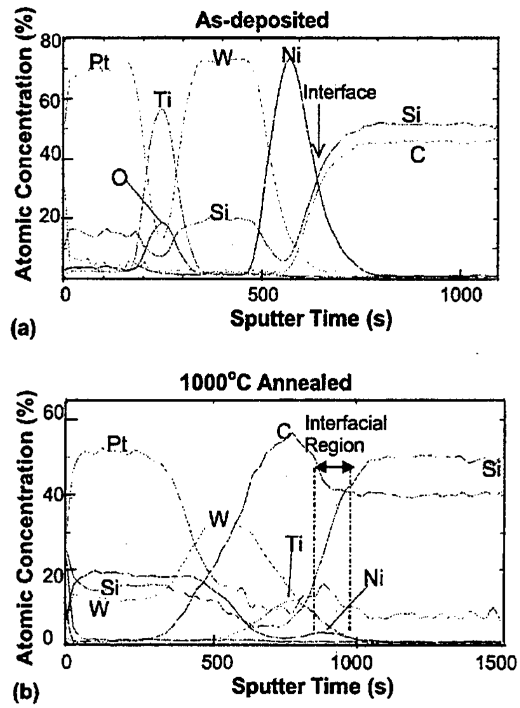

FIG. 2. AES depth profile for (a) the as-deposited and (b) the 1000 °C annealed Ni/WSi/Ti/Pt metallization scheme on *n*-SiC.

(TCA), boiling acetone and methanol, followed by a rinse in de-ionized water. The samples were rapid thermal annealed in a AG Associates rapid thermal annealing system for 30 s at 900, 950, and 1000 °C. Material characterization was performed on the as-deposited and annealed samples. The contacts electrical quality was evaluated via current–voltage characteristics using a HP 4140B semiconductor test system. Auger electron spectroscopy (AES) was used to chemically depth profile the different contact elements. The AES data were acquired using a Perkin–Elmer PH1660 scanning Auger microscope. A 5 keV electron beam was used to stimulate Auger transitions within the sample. In addition, a 4 keV Ar^+ ion beam was used to simultaneously sputter etch the surface. In this way, elemental information as a function of depth was collected, that is, an Auger depth profile. The resulting data were plotted as atomic concentration versus sputter time. Field emission scanning electron microscopy (FESEM) was utilized to assess the contact surface morphology, contact–SiC interface uniformity, and film microstructure. Cross-sectional and plan-view images were acquired with a Hitachi S4500 FESEM. A 45° sample stub combined with the stage tilt (45° maximum) was employed for the cross-sectional imaging. The imaging was executed without conductive coatings in both secondary and backscatter electron modes at magnifications ranging from 15k× to 150k×. The surface morphology was also examined and quantified by a Digital Instrument's Dimension 3000 atomic force microscope (AFM) using tapping mode with amplitude modulation. The contact structure was analyzed by glancing-angle (5°) x-ray diffraction (GAXRD). The GAXRD patterns were recorded on a Siemens D-5005 powder diffractometer using Cu $K\alpha$ radiation at 50 kV and 40 mA. Data were acquired in the range of 20°–100° at a scan rate of 1.8° 2θ/min.

III. RESULTS AND DISCUSSION

The electrical, structural, and chemical properties of sputtered Ni/WSi/Ti/Pt Ohmic contacts to *n*-SiC have been investigated as a function of annealing temperature. The *I–V* characteristics of the as-deposited and annealed composite contacts to *n*-SiC are displayed in Fig. 1. The as-deposited sample exhibited rectifying behavior suggestive of a large barrier height, typically 1 eV or greater. Annealing at 900 °C caused the *I–V* characteristics to move toward Ohmic behavior. Ohmic behavior is demonstrated by *I–V* characteristics which possess linear characteristics with small resistance and are symmetric with reversal of voltage polarity.[17] The contacts became fully Ohmic after the 950 °C anneal. A further reduction in resistance, and the best Ohmic behavior, was achieved after annealing at 1000 °C. Thus, annealing at temperatures between 900 and 1000 °C significantly enhanced the current conduction through the contacts.

In order to assess and understand the contacts electrical characteristics, AES elemental depth profiles, GAXRD, and field emission SEM microstructural analyses were performed on the as-deposited and annealed samples, The AES depth profiles for the as-deposited and 1000 °C annealed samples are displayed in Figs. 2(a) and 2(b). In the case of the as-deposited Ni/WSi/Ti/Pt composite contact the layer structure between each of the contact metallizations remains distinct. Figure 2(a) clearly shows that the top surface is composed of pure Pt. Underlying the Pt is a very well resolved Ti layer. The Ti layer shows signs of oxidation as evidenced by the oxygen signal peaking at ~18 at. % at a sputter time of 250 s. The WSi and Ni layers are very distinct and show no evidence of mixing. The interface between Ni and SiC substrate is chemically abrupt; that is, there is no evidence of an interfacial oxide or interfacial chemical reactions upon sputter deposition. The AES depth profile of the 1000 °C annealed sample is shown in Fig. 2(b). The individual contact metal layers are no longer distinct. Extensive intermixing has occurred in response to the 1000 °C heat treatment. A minimum of four layers are present within the contact metallization. The top or outermost layer is dominated by Pt, Ni, Si, and W signals and most likely consists of several phases or alloys. Transmission electron microscopy (TEM) is needed

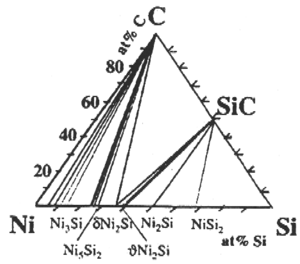

FIG. 3. Isothermal section of the Ni–SiC–C ternary phase diagram at 850 °C (Ref. 14).

to discern the exact composition, structure, and spatial location of the phases which compose the outermost contact layer. Underlying the surface alloy zone is a layer speculated to be composed predominately of tungsten carbide. Beneath the tungsten-based layer is a region where the carbon signal displays a strong peak, 55 at. %, at a sputter time of 750 s. The position of the carbon peak coincides with the maximum in the Ti signal and is suggestive of titanium-carbide phase formation. The presence of TiC was confirmed by the GAXRD analysis. GAXRD analysis (not shown) on the 1000 °C annealed sample revealed peaks at 41.7, 60.45, 72.35, and 90.8° 2θ, which correspond to 2.16, 1.52, 1.30, and 1.09 Å d spacings for TiC. Further evidence for TiC formation manifests from Ti-based contacts to SiC, where TiC was reported to be the stable phase above 700 °C.[14–16] The 20–80 at. % decay of the Si signal, between 850 and 950 s sputter time, defines the metal–SiC interfacial region. Within this designated interfacial region exists a peak in the Ni signal. We suggest this to be evidence of a limited reaction region between Si and Ni resulting in Ni_2Si phase formation at the metal–SiC interface. Within this same area is a Pt peak, which has been attributed to noise at the Pt energy level. GAXRD data also support the existence of the Ni_2Si phase. The GAXRD analysis (not shown) detected peaks at 31.24°, 32.78°, 33.4°, 39.5°, 43.91°, 45.78°, 49.21°, 66.76°, and 75.37° 2θ, which correspond to the d spacings of 2.86, 2.73, 2.68, 2.28, 2.06, 1.97, 1.85, 1.39, and 1.25 Å for δNi_2Si. It is well documented for Ni contacts on SiC that the SiC dissociates due to the strong reactivity of nickel above 400 °C, and that at ~950 °C the Ni_2Si stable phase is formed leading to carbon accumulation both at the interface and in the metal layer.[7,11] Additionally, the 850 °C isothermal section of the Ni–SiC–C ternary phase diagram (Fig. 3) is characterized by the absence of Ni–C compounds and therefore determined by the nickel-silicide, δNi_2Si (orthorhombic phase), which is in equilibrium with both C and SiC.[14] In this ternary phase diagram no tie line Ni–SiC exists, therefore, Ni is not in thermodynamic equilibrium with SiC. Thus, the AES profile data, GAXRD results, and the high temperature Ni–SiC phase equilibria, strongly support the existence of the Ni–Si reaction product, Ni_2Si, spatially adjacent to the SiC substrate.

The AES depth profile for the 1000 °C annealed composite contact indicates that both the WSi and the Ti layers served to confine the residual carbon which was released from the dissociation of the SiC during the annealing process. These reactions, W–C and Ti–C reactions, are extremely desirable from the standpoint of device reliability. Carbon inclusions at the metal–SiC interface and within the Ni_2Si contact layer are considered a potential source of electrical instability, especially after prolonged operation of the devices at high temperatures.[18] At elevated temperatures, redistribution of carbon inclusions will arise, resulting in significant degradation of the contact's electrical and microstructural properties.[19] Thus, the WSi and Ti layers served to mitigate carbon segregation at the metal–SiC interface. However, cross-sectional transmission electron microscopy observations are necessary for accurate interfacial analysis and complete chemical and spatial phase determination.

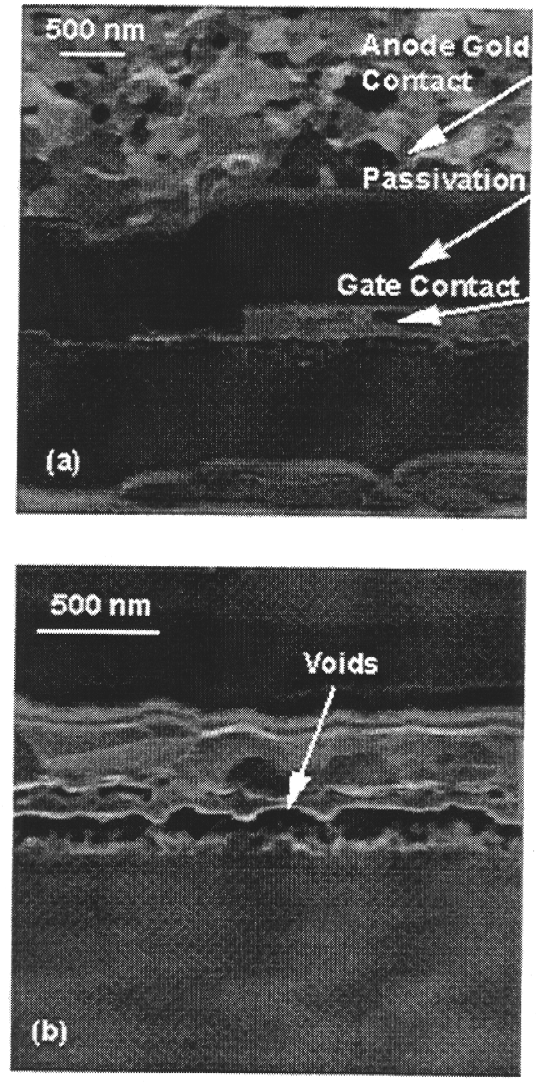

FIG. 4. Ni contact to n-SiC, (a) micrograph of the gate contact and (b) an enlargement of the gate contact showing interfacial voiding and roughness.

Carbon inclusions/segregation are not the only reason for high power and temperature device operation reliability problems. The microstructure of the contact–SiC interface and nature of the contact surface both strongly influence de-

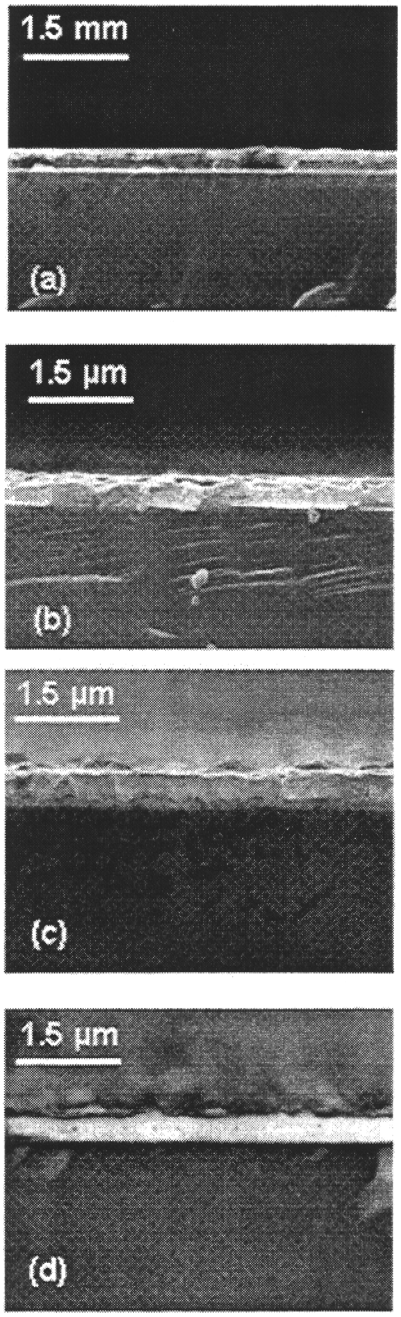

FIG. 5. Cross-sectional secondary electron field emission SEM micrographs of the (a) as-deposited, (b) 900 °C, (c) 950 °C, and (d) 1000 °C annealed Ni/WSi/Ti/Pt Ohmic contacts to *n*-SiC.

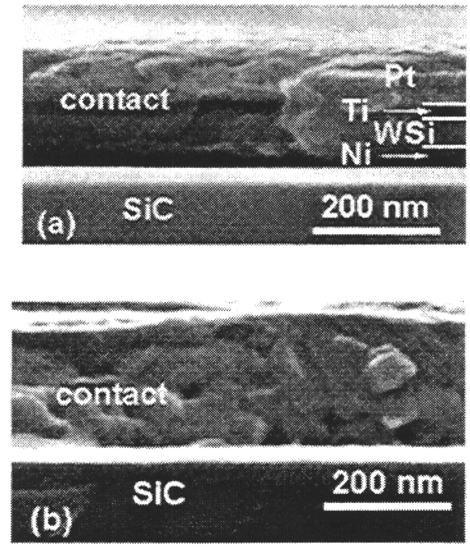

FIG. 6. High magnification field emission SEM micrographs of the (a) as-deposited and (b) 1000 °C annealed Ni/WSi/Ti/Pt composite Ohmic contacts to *n*-SiC.

vice operational reliability. It has been established that annealing of Ni contacts on SiC causes extensive voiding (Kirkendall voids) at the original metal–SiC interface, a contact thickness which has been substantially expanded, and extreme surface roughness.[7,11] Figure 4 shows a typical FESEM cross-sectional image of a Ni–SiC Ohmic contact, that is, a gate contact in a thyristor power device. This micrograph clearly illustrates the heavily voided rough interface morphology, and extreme contact surface roughness (on the order of tens of nanometers) of this Ni–SiC Ohmic contact after annealing at 950 °C. The voids at the interface will cause internal stress and possible delamination of the contact layer, which will compromise device reliability.[11] The internal stress and contact delamination will be significantly amplified under the extreme thermal and electrical stresses typical of the power device operational environment and will ultimately result in device failure. For device applications, Ohmic contacts must be wire bonded to a die package. A rough surface morphology (as illustrated in Fig. 4) will most likely cause wire bonding difficulty and/or failure under the extreme thermal fatigue during high power and high temperature device operation.[7,10]

Figures 5(a)–5(d) display the FESEM secondary electron cross-sectional images of the as-deposited and annealed contacts to SiC. The metal–SiC interfaces are morphologically abrupt and show no evidence of void formation or contact delamination as a result of the annealing process up to 1000 °C. Figures 6(a) and 6(b) display the high magnification (150k×) secondary electron images of the as-deposited and 1000 °C annealed contacts. The distinct metal layers in the as-deposited contact are noted in Fig. 6(a). Comparison of the as-deposited and 1000 °C annealed FESEM images in Fig. 6 not only confirms the abrupt void free interface morphology but also reveals that there is minimal increase (<6%) in contact thickness as a result of annealing. Suppression of contact expansion during annealing is due to restricted interfacial contact growth, that is, a narrow Ni–SiC reaction zone. Specifically, deposition of a thin Ni layer, 40 nm, as opposed to the usual 100–200 nm of Ni traditionally employed results in a significantly limited Ni–SiC reaction zone. This mitigated contact growth after heat treatment makes the Ni/WSi/Ti/Pt composite contact an excellent choice for device designs which posses shallow *p-n* junctions. Plan-view FESEM micrographs of the as-deposited

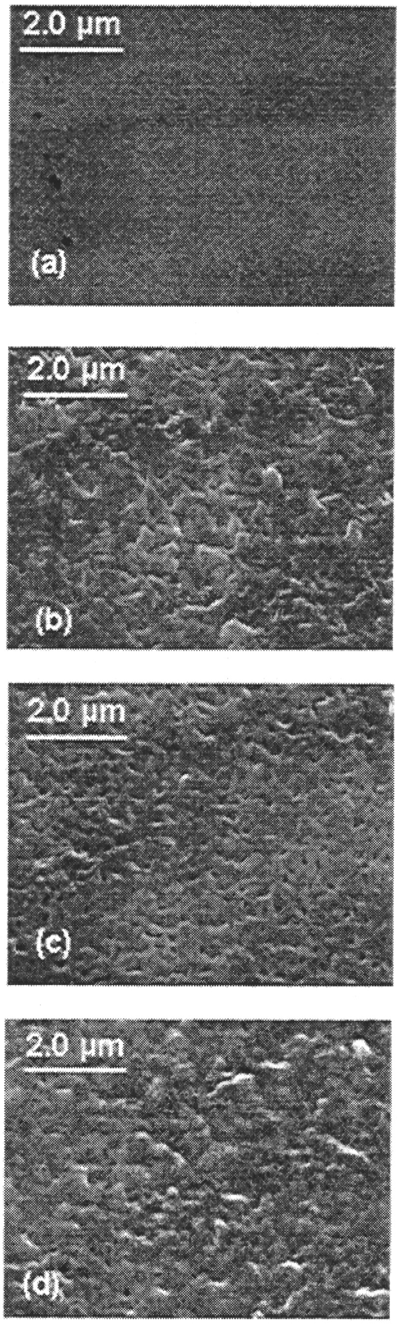

FIG. 7. Plan-view field emission SEM micrographs of the (a) as-deposited, (b) 900 °C, (c) 950 °C, and (d) 1000 °C annealed Ni/WSi/Ti/Pt composite Ohmic contact to n-SiC.

and annealed contacts are presented in Figs. 7(a)–7(d). The as-deposited contact surface, Pt layer, appears homogeneous and smooth. The annealed surfaces remain smooth and show evidence of grain growth. Quantitative analysis of surface roughness, an AFM plot of rms surface roughness as a function of annealing temperature, is displayed in Fig. 8. This extreme smoothness of the as-deposited contact surface is substantiated by a rms surface roughness value of 0.079 nm.

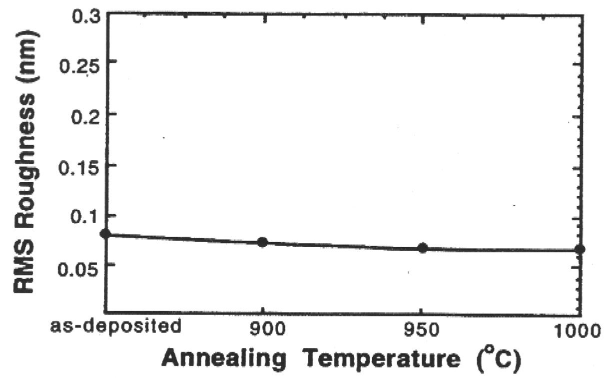

FIG. 8. AFM data of the Ni/WSi/Ti/Pt contact as a function of annealing temperature.

This value remains essentially constant throughout all the heat treatments. Thus, the surface morphology of the annealed Ni/WSi/Ti/Pt composite contact possesses the atomic scale smoothness required for strong reliable wire bonding and should maintain excellent wire-contact mechanical durability during high power and high temperature device operation.

IV. CONCLUSIONS

In conclusion, we have achieved excellent electrical properties for sputtered Ni/WSi/Ti/Pt Ohmic contacts to n-SiC annealed between 950 and 1000 °C for 30 s. The excellent electrical properties were paralleled by the formation of a narrow Ni_2Si interfacial reaction zone, minimal contact broadening, and a smooth, abrupt, and void free contact–SiC interface. The residual carbon, resultant from the reaction of SiC with the overlying Ni, was confined by Ti-carbide and W-carbide phases spatially distant from the contact–SiC interface. Thus, the detrimental effects of contact delamination due to stress associated with interfacial voiding, and wire bond failure due to extreme surface roughness, have been eliminated for this composite Ohmic contact. Additionally, electrical instability associated with carbon inclusions at the contact–SiC interface after prolonged high temperature and high power device operation has also been eliminated. Thus, the electrical, structural, and compositional integrity of this composite contact bodes well for its reliability under the influence of high temperature and high power operational stress environments. Future work will focus on TEM analysis in order to refine the nature of the contact microstructure and define the spatial extent of reaction products. Additional studies will focus on static and acute pulsed thermal fatigue testing in order to quantify the thermal stability of this contact.

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13. ABSTRACT *(Maximum 200 words)*

Ni/WSi/Ti/Pt Ohmic contacts to *n*-SiC were investigated as a function of annealing temperatures up to 1000 °C. Annealing at temperatures between 950 and 1000 °C yielded excellent Ohmic behavior. At these temperatures the contact–SiC interface was smooth, defect free, and characterized by a narrow Ni_2Si reaction region. The annealed contacts possessed atomically smooth surface morphologies and exhibited minimal contact expansion. The residual carbon, resultant from SiC decomposition and reaction with Ni to form Ni_2Si, was constrained by reaction with the WSi and Ti layers forming carbide phases of W and Ti spatially distant from the metal semiconductor interface. Our results demonstrate that the Ni/WSi/Ti/Pt composite Ohmic contact maintains the desirable electrical properties associated with Ni contacts and possess excellent interfacial, compositional, and surface properties which are required for reliable high power and high temperature device operation.

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