A Novel Tungsten–Nickel Alloy Ohmic Contact to SiC at 900 °C

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***Abstract*—A novel tungsten–nickel ohmic contact metallization on 4H-SiC and 6H-SiC capable of surviving temperatures as high as 900 °C is reported. Preliminary results revealed the following: 1) ohmic contact on n-type 4H-SiC having net doping levels (N_d's) of 1.4 and 2×10^{19} cm^{-3}, with specific contact resistances ρ_{sNd}'s of 7.69×10^{-4} and 5.81×10^{-4} $\Omega \cdot$cm^2, respectively, after rapid thermal annealing (RTA), and 5.9×10^{-3} and 2.51×10^{-4} $\Omega \cdot$cm^2, respectively, after subsequent soak at 900 °C for 1 h in argon, and 2) ohmic contact on n- and p-type 6H-SiC having $N_d > 2 \times 10^{19}$ and $N_a > 1 \times 10^{20}$ cm^{-3}, with $\rho_{sNd} = 5 \times 10^{-5}$ and $\rho_{sNa} = 2 \times 10^{-4}$ $\Omega \cdot$cm^2, respectively, after RTA, and $\rho_{sNd} = 2.5 \times 10^{-5}$ and $\rho_{sNa} = 1.5 \times 10^{-4}$ $\Omega \cdot$cm^2 after subsequent treatment at 900 °C for 1 h in argon, respectively.**

***Index Terms*—Amphoteric, high temperature, nickel, ohmic contacts, silicon carbide, tungsten.**

I. Introduction

SILICON carbide (SiC) sensors and electronics have been demonstrated to operate at 600 °C and 500 °C, respectively [1], [2]. However, the need to instrument engines at higher temperatures demands more robust and reliable devices. A major impediment to such an objective is the nonexistence of an ohmic contact metallization scheme to SiC that can operate reliably for prolonged periods at temperatures higher than 600 °C. Rastegaeva *et al.* studied a W/6H-SiC (n-type) scheme up to 677 °C and reported an ohmic contact, with specific contact resistivity, ρ_s, of between 2×10^{-3} and 7×10^{-4} $\Omega \cdot$cm^2 [3]. However, time-dependent evaluation was not performed to determine the long-term stability of the contacts. Marinova *et al.* used X-ray photoelectron spectroscopy (XPS) to investigate the interface chemistry and measured electrical contact characteristics of separate Ni-based metallization on n-doped 6H-SiC ($N_d = 1-1.8 \times 10^{18}$ cm^{-3}) and 4H-SiC ($N_d = 10^{19}$ cm^{-3}) after annealing at 950 °C in nitrogen ambient [4]. They showed that an ohmic contact was formed after annealing and remained relatively stable after aging in nitrogen ambient for 100 h at 500 °C. Kakanakova-Georgieva *et al.* annealed WN/4H-SiC up to 1200 °C and used XPS to study the interface chemistry [5]. The formation of W_2C and W_5Si_3 was reported, with the contacts becoming rectifying. In the work reported by Liu *et al.*, Ni/W metallization was sequentially deposited on p-type 4H-SiC and 6H-SiC ($N_a = 10^{19}$ cm^{-3}) epilayers [6]. The ρ_s values obtained are in relative agreement with those reported in this letter. In addition, the authors aged one of the samples (polytype not reported) in vacuum for 300 h at 600 °C and showed slight decrease in ρ_s.

This letter presents the preliminary results of the investigation of W50:Ni50 alloy metallization, with the primary goal of demonstrating a simultaneous ohmic contact to both n- and p-type 4H-SiC and 6H-SiC, in addition to achieving stability at 900 °C. The ohmic contact to p-type epilayers is traditionally enhanced by ion implantation by creating a degenerately doped layer. However, this process is known to be costly and time consuming. It also induces damage to the lattice, and implant activation is sometimes incomplete, thus resulting in ohmic contact degradation.

II. Experimental Setup

Tungsten–nickel (W50:Ni50 at.%) alloy contacts were fabricated on commercially grown 2 μm-thick homoepitaxial 4H-SiC and 6H-SiC epilayers of n- and p-type conductivities on high-resistivity (3–11 $\Omega \cdot$cm) p-type substrates. For the n-type 4H-SiC and 6H-SiC and the p-type 6H-SiC, the common transfer length method (TLM) test structure [7] was used to evaluate the contacts fabricated on the epilayer mesas. For the p-type 4H-SiC ($N_a > 2 \times 10^{19}$ and $N_a = 1.6 \times 10^{19}$ cm^{-3}), the metallization was fabricated directly on the epilayers without TLM structures to allow for only the qualitative evaluation of the I–V characteristics. In all cases, irrespective of the epilayer resistivity, the p-type substrates used always had a much higher resistivity than the epilayer in order to minimize substrate leakage current paths that could skew the results. The epilayer impurity concentrations were as reported by the SiC wafer vendor. The TLM structure consisted of five rectangular contact pads. Each sample set has three TLM subsets, with each subset having rectangular dimensions/(edge-to-edge distances) of 100×40 μm^2/(35, 70, 105, and 140 μm), 100×45 μm^2/(30, 60, 90, and 120 μm), and 100×50 μm^2/(25, 50, 75, and 100 μm). The TLM isolation mesas were patterned with a parallel-plate reactive ion etcher using SF_6 and Ar chemistry and an Al mask. The samples were solvent cleaned, immersed in equal volume of $H_2O_2 : H_2SO_4$ solution for 15 min, HF for 1 min, and followed by wet oxidation at 1000 °C to obtain an oxide layer of approximately 2000 Å. Contact vias were etched into the oxide to expose the SiC epilayer.

Manuscript received April 8, 2010; revised May 3, 2010; accepted May 5, 2010. Date of publication June 28, 2010; date of current version July 23, 2010. This work was supported by the NASA Fundamental Aeronautics Program under the Hypersonic and Supersonic Projects. The review of this letter was arranged by Editor S.-H. Ryu.

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Digital Object Identifier 10.1109/LED.2010.2050761

TABLE I
QUALITATIVE AND QUANTITATIVE ELECTRICAL CHARACTERISTICS OF W50:Ni50 METALLIZATION ON n- AND p-TYPE 4H-SiC AND 6H-SiC AFTER VARIOUS PROCESS STEPS

Polytype/Doping Level (cm^{-3})	ρ_s (Ω-cm^2) As Deposited	Post-RTA	Post 900 °C, 60 min.
4Hn/>2x10^{19}	1.7x10^{-1}	5.81x10^{-4}	2.51x10^{-4}
4Hn/1.4x10^{19}	1.6x10^{-2}	7.69x10^{-4}	5.9x10^{-3}
4Hp/>2x10^{19}	Ohmic	Ohmic	Ohmic
4Hp/1.6x10^{19}	Ohmic	Rectifying	Rectifying
6Hn/>2x10^{19}	Rectifying	5x10^{-5}	2.5x10^{-5}
6Hp/>1x10^{20}	5x10^{-3}	2x10^{-4}	1.5x10^{-4}

The contact metal was then deposited from a tungsten–nickel (W50:Ni50 at. %) alloy target and was patterned and etched to form the desired electrical contact to the SiC epilayers. The contact metal evaluated consisted of a sputter-deposited 100-nm film, followed by a 20-nm Si capping layer to prevent premature oxidation of the alloy. The samples were annealed in a rapid thermal annealer at 1000 °C for 5 s, at a pressure of 210 mtorr in evacuated argon. A series of current–voltage (I–V) and ρ_s measurements was conducted on each TLM subset as-deposited, after rapid thermal annealing (RTA), and after aging over time at 900 °C in Ar ambient. Only I–V measurements were performed on non-TLM samples.

III. RESULTS AND DISCUSSION

The summary results of the specific contact resistance measurements and the I–V characteristics are shown in Table I. An ohmic contact was achieved after RTA in all the subsets, except one sample set, for all the metallization runs. The ρ_s values reported were obtained by averaging across the three TLM subsets from each sample. The ρ_s values for the highly doped n-type 4H-SiC ($> 2 \times 10^{19}$ cm^{-3}) and 6H-SiC ($> 2 \times 10^{19}$ cm^{-3}) samples improved significantly after the RTA processes and remained relatively unchanged after subsequent thermal treatment at 900 °C for 1 h in argon ambient. The results obtained on the p-type 6H-SiC epilayers also showed improved ρ_s after 900 °C soak for 1 h. For the two p-type non-TLM 4H-SiC epilayer samples, an ohmic contact was achieved on the less doped ($N_a = 1.6 \times 10^{19}$ cm^{-3}) samples in as-deposited condition but became rectifying after RTA and thereafter. However, the heavily doped sample ($N_a > 2 \times 10^{19}$ cm^{-3}) exhibited ohmic characteristics throughout, as shown in the I–V plot of Fig. 1. In these cases, the absence of TLM structures precluded quantification of ρ_s. The observed ρ_s increase on the lesser doped n-type 4H-SiC and the decrease in the I–V slope of the p-type 4H-SiC after the 900 °C soaks are currently not understood. The Fermi-level pinning effect could only be speculated.

The W50:Ni50 alloy, upon annealing, appeared to exhibit a *pseudoamphoteric ohmic contact* behavior by virtue of its simultaneous ohmic contact formation on both n- and p-type SiC. It is not yet clear if this behavior could be attributed to enhanced field emission. Pelletier *et al.* found the Fermi energy (FE) level to be approximately 0.29 eV above the valence band for the p-type 6H-SiC having a doping level of about 1×10^{19} cm^{-3} [8]. Also, using the effective hole mass of $1.2m_o$ for the p-type 4H-SiC ($m_o = 1.67 \times 10^{-27}$ kg) from Raynaud *et al.* [9], the FE corresponding to $N_a > 2 \times 10^{19}$ cm^{-3} was approximately 0.31 eV above the valence band. These values would suggest nondegenerate doping levels in the p-type 6H-SiC and 4H-SiC, respectively. The work functions (WFs) of W_xC_y compounds have been reported to be between 4.9 and 6.3 eV [10], [11], which are greater than the WF of the p-type 6H-SiC doped at $> 2 \times 10^{19}$ cm^{-3} that was reported in [8] to be about 4.85 eV. This would, in principle, satisfy the basic condition for W_xC_y to form an ohmic contact to the p-type 6H-SiC, assuming the absence of interface charge pinning. Based on these arguments, it would appear that a combination of enhanced tunneling and thermionic-emission charge transport mechanisms coexists [12]. Conversely, nickel silicide compounds, such as those reported in [5] and others reported in the literature, form ohmic contacts to the n-type SiC. Auger electron spectroscopy (AES) analyses described in detail hereinafter indicate the existence of a W_xC_y-Ni_xSi_y composite matrix at the SiC interface after RTA. Although yet to be fully understood, the presence of W_xC_y and Ni_xSi_y mixtures at the n- or p-type SiC interface appears to satisfy the condition for a *pseudoamphoteric ohmic contact*. The formation of a simultaneous ohmic contact to both n- and p-type SiC would have a significant impact in terms of reducing the cost and process time associated with the fabrication of SiC-based bipolar devices.

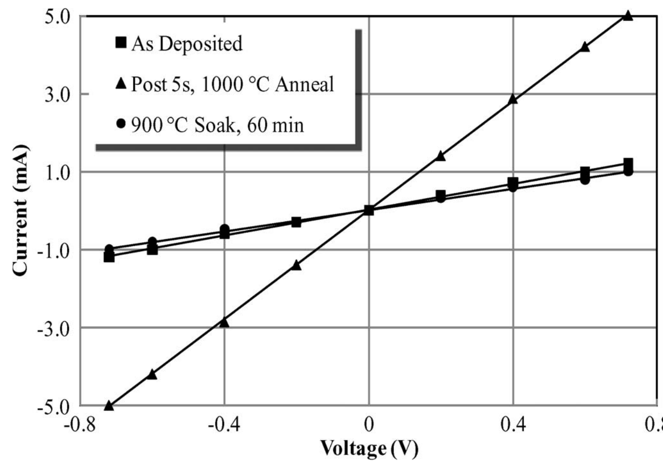

Fig. 1. As-deposited, post-RTA, and post-900 °C 60-min-soak I–V characteristics of W50:Ni50 alloy metallization on non-TLM p-type 4H-SiC epilayers having a doping level of $N_a > 2 \times 10^{19}$ cm^{-3}.

The AES depth profile of the as-deposited metallization is shown in Fig. 2(a). After RTA, the AES depth profile shown in Fig. 2(b) indicates that the nickel in the alloy had reacted with both the top surface Si layer and the SiC substrate to form Ni_xSi_y, thus freeing the carbon that reacts with tungsten. It is possible that W_xSi_{1-x} was also present, although the thermodynamics favor NiSi and WC formation at 1000 °C temperature [13]. However, other analytical methods would be

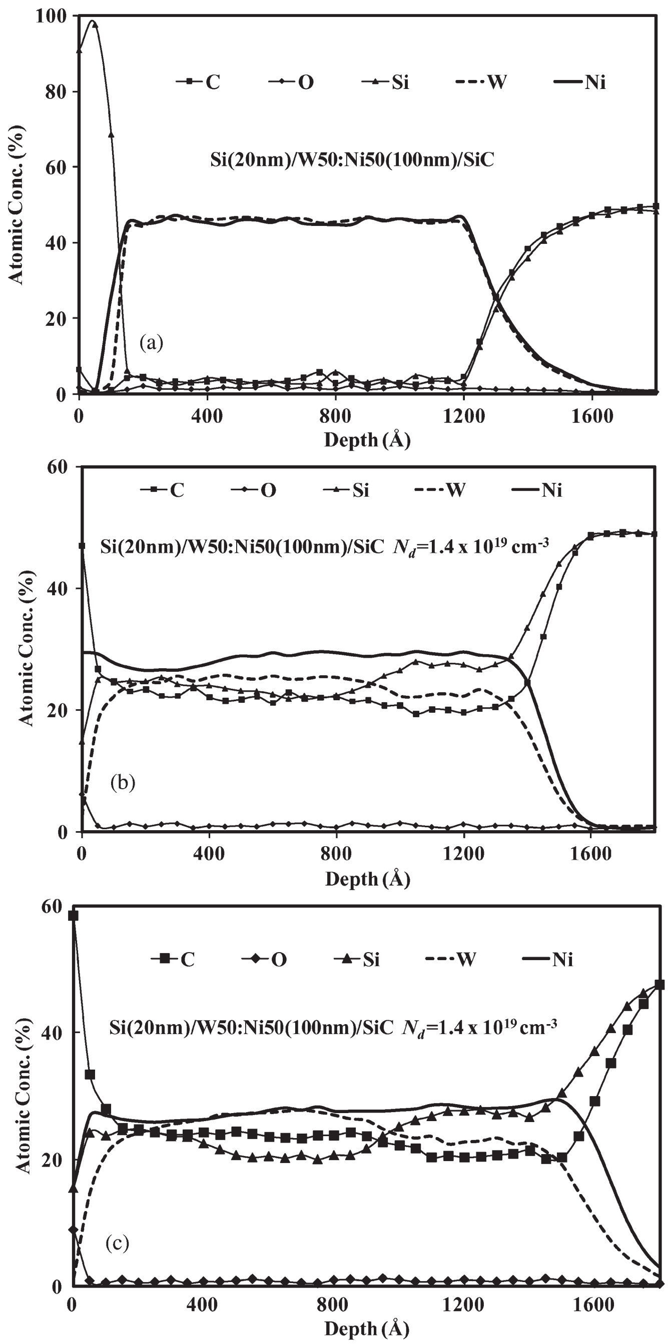

Fig. 2. AES depth profile of W50:Ni50 alloy metallization on SiC epilayer. (a) As deposited. The top silicon layer prevents the oxidation of tungsten. (b) After RTA. The SiC reaction zone indicates the formation of nickel silicide, tungsten carbide, and, possibly, tungsten silicide. (c) After RTA and 1-h furnace soak at 900 °C in Ar ambient. The SiC reaction zone shows little change.

applied to more specifically identify the carbide and silicide phases that are present at the SiC interface. The Auger profile after the 900 °C soak for 1 h [Fig. 2(c)] showed little change from the previous one.

IV. Conclusion

The preliminary results of W50:Ni50 contact metallization demonstrate an ohmic contact to highly doped n- and p-type 4H-SiC and 6H-SiC with contact resistivities shown to be stable even after thermal soak at 900 °C for 1 h. An important aspect of these results was the observed *pseudoamphoteric ohmic contact* behavior of this metallization scheme. The fundamental semiconductor physics to explain this behavior is currently being studied.

Acknowledgment

The authors would like to thank C. Blaha and K. Laster of the NASA Glenn Research Center Microsystems Fabrication Laboratory for their contribution to the success of this work.

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