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Thermal and electrical properties of Au/B_4C, Ni/B_4C, and Ta/Si contacts to silicon carbide

J.O. Olowolafe[a,*], J.S. Solomon[b], W. Mitchel[c], W.V. Lampert[d]

[a]Department of Electrical and Computer Engineering, University of Delaware, Newark, DE 19716, USA
[b]University of Dayton Research Institute, 300 College Park, Dayton, OH 45469, USA
[c]Air Force Research Laboratory, Materials and Manufacturing Directorate (AFRL/ML) Wright Patterson AFB, OH 45433, USA
[d]US Army Research Office PO Box 12211 Research Triangle Park, NC 27709, USA

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Abstract

The role of silicon and boron carbide interface layers on thermal stability and electrical properties of tantalum, gold, and nickel contacts to 6H- and 4H-n-silicon carbide are presented in this report. Thin Ta/Si, Au/B_4C, and Ni/B_4C layers were deposited on SiC using electron-beam evaporation or sputter-deposition techniques. The structures were annealed either in ultra-high vacuum or in N–H ambient, at temperatures ranging from about 400 to 1150 °C. The samples were characterized using atomic force microscopy for surface topography, auger electron spectrometry for depth profiling, and glancing angle X-ray diffraction for microstructure and phase identification analyses. Transmission line model structures for current–voltage measurements and contact resistance evaluation were prepared using photolithography and lift-off techniques. Our results indicate that Ta in the Ta/SiC system decomposes SiC at about 800 °C, forming tantalum carbide with the accumulation of silicon at the TaC/SiC interface. In the Ta/Si/SiC system decomposition of SiC also occurs about the same temperature resulting in the structure TaC/Si/SiC. The $Au/B_4C/SiC$ system appears to be the most thermally stable with the lowest specific contact resistance of about 1×10^{-6} Ω cm^2 for samples heat-treated above 1050 °C for 30 min.

Keywords: Silicon carbide; Boron carbide; Gold; Tantalum

1. Introduction

Progress on silicon carbide technology has suffered a setback because of materials- and process-related problems [1]. Such problems include reliable, high-temperature, low-resistance ohmic contacts and thermally stable metal–SiC systems. Because of this, the goal of commercialized high-temperature, high-frequency devices for various civil and military applications is far from being achieved. Typical is the effort to incorporate advanced SiC electronics into military aircraft, the More Electric Aircraft initiative, part of a larger effort referred to as the More Electric Initiative. This application covers not only military systems but commercial systems such as electric vehicles, ships, and power systems as well [2]. Other applications where high temperature plays a major role include high-frequency radar and communication systems that could be used in aerial vehicles, SiC-based sensors for automotive, aeronautic, or environmental applications. Apart from high-temperature applications where thermal stability is a crucial requirement, obtaining ohmic contacts on SiC often requires high-temperature annealing, as documented in many articles [3–6].

Metals that are commonly used as contacts, such as Al and Ni, to p- and n-type SiC, respectively, are very reactive and thermally unstable either because of a low-melting point (~660 °C for Al) or thermodynamic properties. For thermal stability and low resistance at the same time multi-layered contacts such as Al/Ti, Al/Si, W/Pt/Al, Au/TaC, Pt/TaC, and W/WC/TaC on SiC substrates are often prepared [7–11]. While most articles have been written on electrical proper-

* Corresponding author. Tel.: +1 302 8314272; fax: +1 302 8314316.
E-mail address: olowolaf@ee.udel.edu (J.O. Olowolafe).

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ties, only a few investigate interface reactions between metals and SiC. But to fully understand the properties of contacts to SiC, reaction properties, thermal stability, and interdiffusion mechanisms between metals and substrates are crucial [12]. This investigation, therefore, focuses on both thermal stability and electrical properties of Ta/Si, Au/B_4C, and Ni/B_4C contacts to SiC.

2. Experimental details

One-sided polished 6H and 4H n-type SiC wafers about 1.3 in. in diameter and 3.5 to 8° off axis were used in this project. The substrates were oxidized and etched in diluted HF prior to metal deposition. Metals were deposited using both electron-beam deposition techniques in an ultra-high vacuum system with a base pressure of about 5×10^{-9} Torr and in a Denton vacuum sputtering system with a base pressure of about 6×10^{-7} Torr. The thickness of Au, Ni, or Ta was varied between 100 to 200 nm while that of B_4C or Si was fixed at about 50–60 nm. The structures were annealed at various temperatures, 400–1150 °C, in various ambient including vacuum, Ar and forming gas (N–H). The surface topography and morphology of these structures, before and after annealing, were evaluated using the atomic force microscopy (AFM). The distribution of elements in the structures was analyzed using Auger depth profiling while glancing-angle X-ray diffraction technique was used to evaluate intermetallic phases and compounds after annealing.

Auger surface and elemental depth profile analyses were conducted with a Physical Electronics scanning Auger microprobe, model 545. A 5 keV electron beam was used for the analyses and a coincident 2 keV argon ion beam was used for sputtering to generate elemental depth profiles.

Samples for electrical measurements were patterned using photolithography and etch-off techniques. Current–voltage (I–V) measurements were used to determine whether contacts were ohmic or not while the specific contact resistances of samples were evaluated using the transmission line model (TLM) technique. Metal patterns for transmission line measurement structures are normally rectangular with progressively increasing separation between adjacent contacts [13–16]. The total resistance, R_T, at adjacent metal contacts was measured as a function of separation, d. R_T is typically linearly dependent on d as $R_T=(\rho_S/Z)\cdot d+R_C$, where R_C is the contact resistance, ρ_S is the sheet resistance and Z is the width of the contact. The plot of R versus d is a straight line from which ρ_S/Z was evaluated. The donor concentration in SiC is therefore calculated from the relation, $\rho_S=1/(q\mu N_d)$, where μ [about 700 cm^2 (Vs)$^{-1}$ for $N_d=1.1\times10^{16}$ cm^{-3} for 6H-SiC] is the mobility of electrons in SiC and q is the charge of an electron.

3. Results and discussion

The microstructure, surface morphology, and interface properties play crucial roles on electrical properties of metal–semiconductor contacts. Thus, it is critical to determine the extent of reaction between different metals and SiC and to evaluate the reaction products. Therefore, Auger electron spectroscopy (AES) was used to systematically characterize the surface and to depth profile the materials distribution in the metal–semiconductor structures both as deposited and after annealing.

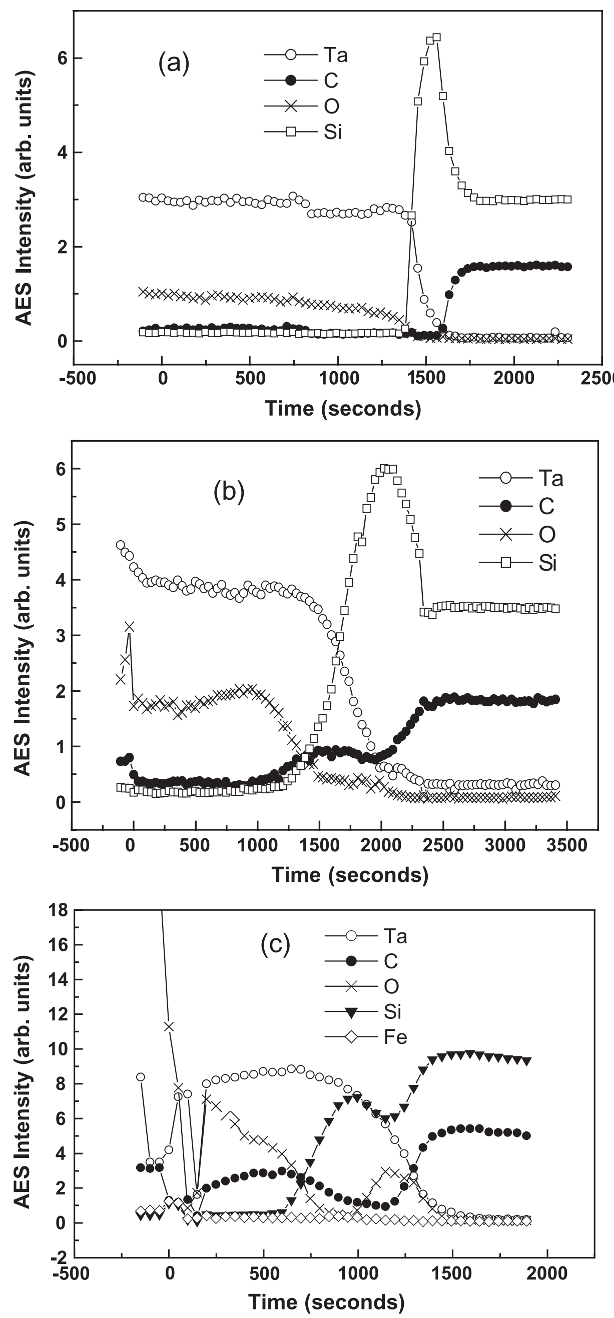

Fig. 1. AES depth profiles of 150-nm Ta/50 nm Si/SiC (a) as-deposited, (b) annealed at 650 °C, and (c) 950 °C.