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Solid state reaction of ruthenium with silicon carbide, and the implications for its use as a Schottky contact for high temperature operating Schottky diodes

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ABSTRACT

A thin film of ruthenium was deposited on n-type-4-hexagonal-silicon-carbide (4H-SiC) so as to study the interface behaviour of the ruthenium Schottky contact with silicon carbide. Ruthenium (Ru) Schottky diode dots were also fabricated by deposition of ruthenium on n-type-4H-SiC which had nickel as a back ohmic contact. The Ru-4H-SiC Schottky barrier diodes (SBDs) and thin films were both annealed isochronally in a vacuum furnace at various temperatures. Rutherford-backscattering-spectrometry analysis of the thin film sample showed evidence of formation of ruthenium silicide (Ru_2Si_3) and diffusion of ruthenium into silicon carbide at annealing temperatures of 700 °C and 600 °C respectively. Raman analysis of the sample that was annealed in a vacuum at 1000 °C showed evidence of the formation of graphite, and Ru_2Si_3. Despite the occurrence of the chemical reactions and diffusion of ruthenium into 4H-SiC, the SBDs were operationally stable up to the final annealing temperature of 1000 °C.

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1. Introduction

Researchers have shown renewed interest in silicon carbide (SiC), owing to the fact that it has superior qualities of a large band gap, a high breakdown electric field, high thermal conductivity, high saturation carrier velocity, and high mechanical strength when compared with silicon. The aforementioned properties make SiC an ideal material for electronic devices operating at extreme temperatures. Four-hexagonal silicon carbide (4H-SiC) and six-hexagonal silicon carbide (6H-SiC) have very similar electrical properties, however, 4H-SiC exhibits superior electronic properties of wider band-gap [1], and higher electron mobility on the *c*-axis when compared with 6H-SiC [2]. This high electron mobility makes it possible for 4H-SiC-based power devices to operate at high frequency [3]. In addition to the above superior qualities, the mastery of step-controlled epitaxy for the homoepitaxial growth of high quality 4H-SiC single crystals [4] has increased the potential for the production of good quality high-power 4H-SiC-based devices.

In this investigation ruthenium (Ru) has been used as a Schottky contact, and nickel as an ohmic contact in the fabrication of Schottky barrier diodes (SBDs). Ru has a high melting point (2250 °C), high chemical stability, low electrical resistance, and a high mechanical resistance to abrasion and fatigue [4]. These properties make Ru a good candidate for Schottky contacts for high temperature operating SBDs. At such high operating temperatures, there is a high possibility of occurrence of chemical reactions and diffusion of elements at the interface of the Schottky contact and SiC. However, there has been limited literature [5–9] on solid state reaction of Ru with SiC, and minimal attempts have been made by researchers in determining the maximum operating temperature of Ru-SiC based Schottky diodes. This study attempts to determine the maximum annealing temperature at which the Ru-4H-SiC SBDs completely degrade and become unusable. The solid state reaction of Ru with 4H-SiC and its linkage with the performance and degradation mechanism of the Ru-4H-SiC SBDs are also investigated.

One of the important parameters of an SBD is the Schottky barrier height (SBH). The SBH determines the electrical character of an ohmic or Schottky contact. An ohmic contact is important for making outside interconnection to a device. A low SBH generally

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creates good ohmic contact while a large SBH will lead to a good Schottky contact [10].

In this study Ru-4H-SiC SBDs with nickel back ohmic contacts, and an Ru-4H-SiC thin film were annealed in a vacuum at various temperatures. The solid state reaction of ruthenium with 4H-SiC was investigated by Rutherford backscattering spectrometry (RBS) and Raman spectroscopy. information on the quality of the SBDs and the maximum annealing temperature before the complete degradation of the SBDs was obtained from the analysis of data on variation of SBH, ideality factor, reverse-saturation current and series resistance of the SBDs with annealing temperature. These data were obtained from current-voltage (IV) and capacitance-voltage (CV*IVCV*) characteristics of the diode.

2. Experimental method

2.1. Introduction

Research has shown that the electrical performance of Schottky contacts on SiC, in addition to physical and chemical properties, is strongly dependent on the quality of the metal–semiconductor interface and the surface preparation prior to metallization [11].

2.2. Preparation of 4H-SiC before depositing the metal contacts

The n-type 4H-SiC wafer from Cree Research Inc. with a thickness of 368 μm, resistivity of 0.021 Ω cm with an epilayer of donor concentration of 1.16×10^{16} cm^{-3} and thickness of 6 μm was prepared for metallization by degreasing, using an ultra-sonic bath for a period of 5 min for each step, in trichloroethylene, acetone and methanol, followed by rinsing in deionised water. The sample was then deoxidized in 10% hydrofluoric acid. The sample was finally rinsed in deionised water and then dried with nitrogen gas before being loaded into the vacuum chamber where 200 nm of nickel (Ni) was deposited on the rough surface of 4H-SiC by vacuum resistive evaporation at a pressure of 10^{-5} mbar. The sample was positioned at a distance of 20 cm above the evaporation crucible, and the deposition rate was 1 Å s^{-1}. After nickel deposition, the sample was annealed in an argon atmosphere in Lindberg Heviduty furnace at a temperature of 1000 °C for 1 min to make the nickel contact ohmic. The annealed sample was then chemically cleaned again in trichloroethylene, acetone and methanol, and deionised water before a 50 nm thick of Ru was deposited on the polished side (Si-face) of the sample by an electron-beam deposition technique through a metal contact mask at 10^{-6} mbar pressure. The metal contact mask was positioned at a distance of 50 cm above the Ru containing carbon crucible. The rate of Ru deposition was 0.1 Å s^{-1}. At the commencement of deposition, the contact mask was initially at room temperature but its temperature rose up to around 100 °C during the deposition process. The Ru film thickness was monitored by Infincon meter until the required thickness of 50 nm was obtained. A number of Schottky contacts of diameter 0.6 mm were fabricated.

The sample for solid state reaction investigation was made by depositing a 50 nm film of Ru on the polished side of n-type 4H-SiC. Before deposition of the Ru film,the n-type 4H-SiC was cleaned through the steps mentioned in the paragraph immediately above. Nickel was not deposited on this sample for microstructure characterisation.

2.3. Solid state investigation, IV and CV characterisation

The Ru-4H-SiC SBDs and thin film were annealed in a vacuum furnace at pressure of less than 10^{-6} mbar at the same time for a period of 1 h at temperatures ranging from 500 °C to 1000 °C. The Ru-4H-SiC thin film was analysed at room temperature after each each annealing step by RBS using helium ions with energy of 1.4 MeV. The sample annealed at 1000 °C was also analysed at room temperature by Raman spectroscopy with excitation laser of wavelength 514.6 nm. Full *IV* and *CV* characterisation of the diodes was performed at an ambient temperature of 24 °C after each annealing process using a 4140B PA meter/DC voltage source by Hewlett Packard, which was interfaced to a LabVIEW-operated computer. The *CV* measurements were done at a frequency of 1 MHz, and the maximum reverse voltage was −2 V. Both the *IV* and *CV* measurement data were automatically saved on the computer by LabVIEW.

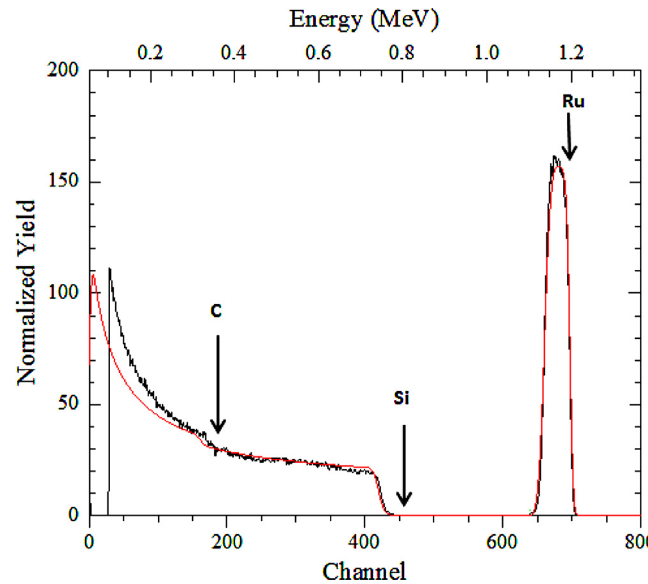

Fig. 1. RBS spectra of as-deposited Ru-4H-SiC film where the red and black plots are the simulated and actual profiles respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

3. Experimental results and discussion

The RBS spectra for as-deposited Ru-4H-SiC thin film, and samples annealed at 600 °C, 700 °C and 800 °C are shown in Figs. 1–4 respectively. The spectra for annealing temperatures of 900 °C and 1000 °C were similar to those of the sample annealed at 800 °C, and therefore their spectra have not been included in the report. The RBS spectra of the as-deposited sample (Fig. 1) and samples annealed at 600 °C and 800 °C (Fig. 2 and Fig. 4 respectively) were simulated using the RUMP [12] and thereafter converted into depth profiles. RUMP is a computer code which requires user entry to fit the raw RBS spectra. This fitting, otherwise known as simulations, gives layer by layer information about the film thickness and composition. The composition and thickness of the deposited film and reaction layers can then be converted to depth profiles. The RBS charging current exhibited some instability during the analysis of the sample annealed at 700 °C, and therefore its spectrum was not simulated. The as-deposited spectrum displays a pure Ru thin film deposited on 4H-SiC (Fig. 1 and Fig. 5). After annealing at 600 °C, a thin intermixed layer of Ru and Si is observed to form at the interface (Fig. 6). The Ru:Si atomic ratio of this layer is found to be 1:1. The carbon released in this case is difficult to observe from the RBS spectra. The raw RBS spectrum for the sample annealed at 700 °C (Fig. 3) indicates the formation of ruthenium silicide (Ru_2Si_3) as evidenced by the appearance of a step on the high energy edge of Si.

After annealing at a temperature of 800 °C, it is observed that the entire deposited Ru layer has reacted with 4H-SiC (Fig. 4). From the RUMP simulations (Fig. 4, and Fig. 7), Si and C can be found on

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