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Ohmic contacts to single-crystalline 3C-SiC films for extreme-environment MEMS applications

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ABSTRACT

This paper describes the ohmic contacts to single-crystalline 3C-SiC thin films heteroepitaxially grown on Si (0 0 1) wafers. In this work, a TiW (titanium–tungsten) film was deposited as a contact material by RF magnetron sputter and annealed through the vacuum and rapid thermal anneal (RTA) process. Contact resistivity between the TiW film and the n-type 3C-SiC substrate was measured by the circular transmission line model (C-TLM) method. The contact phases and interface of the TiW/3C-SiC were evaluated with X-ray diffraction (XRD), scanning electron microscope (SEM) and Auger electron spectroscopy (AES) depth-profiles. The TiW film annealed at 1000 °C for 45 s with the RTA plays an important role in the formation of ohmic contact with the 3C-SiC film and the contact resistance is less than $4.62 \times 10^{-4}\,\Omega\,cm^2$. Moreover, the inter-diffusion at the TiW/3C-SiC interface was not generated during, before and after annealing, and was kept in a stable state. Therefore, the ohmic contact formation technology of single-crystalline 3C-SiC films by using the TiW film is very suitable for high-temperature micro-electro-mechanical system (MEMS) applications.

1. Introduction

Si-micro-electro-mechanical system (MEMS) technology has rapidly been developing as a high-value technology since the last decade. The integrated MEMS from Si micromachining to a compensating circuit can endure up to 120 °C due to the physical properties of Si and can also endure up to 300 °C by Si-on-insulator (SOI) [1]. Recently, the development of MEMS for the expected operational temperature over 500 °C is required at various industrial fields such as transportation machines, engine, space technology (ST), environment technology (ET) and power plants [2].

Among many wide-bandgap semiconductors, the study of silicon carbide (SiC) has been mainly focused on the nano-electro-mechanical system (NENS) for information technology (IT) and bio technology (BT) industries as well as on MEMS for harsh-environment applications because of its high power, high frequency, high temperature, radiation-hard, corrosion-hard and superior electro-mechanical properties [3,4].

The hexagonal 4H- and 6H wafers are easily fabricated in 2 in. diameter, but are very expensive. Nevertheless, cubic β- or 3C-SiC still remains the only choice for low-cost and large-area applications in spite of a higher defect density. Cubic β- or 3C-SiC heteroepitaxially grown on Si wafers is very suitable for the M/NEMS technology using high temperature, high power, high frequency and bio-electrical devices because the electron mobility ($1000\,cm^2/V\,s$) of 3C-SiC is more excellent than its hexagonal SiC (4H-SiC: $950\,cm^2/V\,S$, 6H-SiC: $450\,cm^2/V\,s$) [5,6].

Therefore, we should precede metallization studies with regard to a thermally stable electrode formation to develop M/NEMS applications for IT, BT, ST and ET by using 3C-SiC with these excellent properties. Regarding the property of SiC, Schottky barrier height (SBH), given as a value of 0.1 eV, can be easily formed into good Schottky contacts, but it is very difficult to obtain a lower barrier height for good ohmic contact behavior. Therefore, it is necessary to develop a metal contact formation technique with lower contact resistivity [7].

In order to achieve better adhesion, chemical reactions occurred between the metal and SiC, which can lead to the diffusion of atoms through annealing. Moreover, this diffusion may lower the contact resistance as a result of additional doping of the SiC region close to the metal–SiC interface [8].

To date, a Ni line for n-type SiC and an Al line for p-type SiC have been used as ohmic contact applications of SiC, but aluminum, given its low melting point (660 °C), is not appropriate for high-temperature applications. Nickel has been reported to be a good ohmic contact because it forms silicide with SiC at elevated temperatures. However, the Ni-SiC reaction is also difficult to control to continuously yield lower contact resistance [9,10]. Recently, ohmic contact for high temperature has been studied

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using thermally stable metals such as W, Ti, and Ta. Of them, TiW is a suitable candidate for ohmic contact because it is thermally stable up to 2700 °C and no phase changes occur below this temperature [11].

Therefore, in this work, we evaluated electrical measurements as well as physical properties such as specific contact resistance, current–voltage (*I–V*) characteristic and interfacial reaction Titanium-based ohmic contacts to single-crystalline 3C-SiC according to annealing as a preceding study of development of the M/NENS device applications for high temperatures.

2. Experiments

In this paper, single-crystalline 3C-SiC thin films are heteroepitaxially grown on Si (0 0 1) substrates by APCVD at a high temperature of 1350 °C using a single precursor such as hexamethyl disilane: {CH.36}Si2 (HMDS), which is easily decomposed at low temperature and has no risk of explosions [12].

Usually the linear transmission line model (L-TLM) method, which can easily calculate, is mainly used, but its process of manufacture is very complicated [13]. Therefore, these samples are patterned by the circular transmission line model (C-TLM) method, which results in a simple technology using only one mask level.

Firstly, the free oxides formed on 3C-SiC thin films were removed in (1:3) HF:H_2O solution. Later, to clean the surface acetone, methanol, and DI water were for 3 min, respectively. TiW thin films, of the Ti/W ratio of 10/90 vol/%, are deposited at about 2000 Å on single-crystalline 3C-SiC their films for ohmic contacts by an RF magnetron sputter.

Table 1 summarizes the deposition conditions of TiW thin films. Fig. 1 shows a surface photography of the sample made in this study and the geometry for the contact resistivity measurement of TiW/3C-SiC. Firstly, the TiW/3C-SiC thin films were characterized by using X-ray diffraction (XRD), scanning electron microscope (SEM) and Auger electron spectroscope (AES) depth-profile, respectively, to analyze interfacial mutuality diffusion and some cracks according to annealing. *I–V* characteristics of the circular TLM patterned TiW/3C-SiC thin films were also measured by an HP4155B semiconductor parameter analyzer to evaluate the specific contact resistance.

Tab1e 1
Deposition conditions of TiW thin films

Parameter	Deposition conditions
Target	TiW 2″ diameter
RF power	200 W
Substrate	Single crystalline 3C-SiC film
Target-substrate distance	8 cm
Working gas	Ar: 20 sccm
Substrate temp.	Room temp.
Working pressure	5.0×10^{-2} Torr

3. Results and discussion

Fig. 2 shows that variation of the crystallization for TiW thin films is analyzed by XRD, which is set from 2° to 4° for an angle of incidence, and is injected into a value of 2θ for a route of search to observe diffraction peaks. These results of XRD analysis for TiW thin films are shown in Fig. 2(a–c) using these conditions such as (a) before annealing and (b) after annealing at 1000 °C for 30 min with a vacuum furnace, and (c) at 1000 °C for 45 s with RTA, respectively. A Ti peak is much stronger than a TiW peak before annealing. By the annealing process, the Ti peak decreased, but a recombined TiW peak increased. Especially, in an RTA process, most Ti are recombined as TiW.

The crack of TiW thin films deposited on 3C-SiC substrates by the annealing process was analyzed with SEM. The surface SEM images of TiW thin films were shown in Fig. 3(a) before annealing, (b) using the vacuum at 1000 °C, and (c) the RTA at 1000 °C. As SEM images, before and after annealing, there were no cracks on TiW deposited on SiC.

Fig. 4 shows the AES depth-profile to analyze the interfacial mutuality diffusion and stability of TiW/3C-SiC before and after annealing. After annealing, it was found to be a stable state, which hardly changed in the interfacial TiW/3C-SiC. Fig. 4(a) shows little O_2 on the surface layer, but Fig. 4(b and c) show that much O_2 on TiW is diffused outside by annealing. Increasing Ti and O_2 showed that the Ti and O_2 of TiW react with each other at high temperatures.

In case of exposure of TiW as the ohmic contact at high temperature, it is considered that the contact characteristic is deteriorated owing to the oxidation of Ti. Therefore, the formation of the oxidation film should be avoided for ohmic contact. We consider that TiW/3C-SiC can be used as ohmic contact applications if Au or Pt is used as anti-oxidation films [14].

Fig. 5 shows the *I–V* characteristics of TiW deposited on 3C-SiC thin films, which have heteroepitaxially grown on Si (0 0 1) substrates according to the annealing conditions. Before and after annealing, the TiW/3C-SiC contacts were observed as the Schottky and ohmic characteristics, respectively. Moreover, the RTA system was relatively more excellent than the vacuum furnace, as shown by one of the samples obtaining the best ohmic behavior at 1000 °C for 45 s.

The results of the above SEM and AES exhibited good ohmic contact behavior owing to the recombination of the TiW thin films

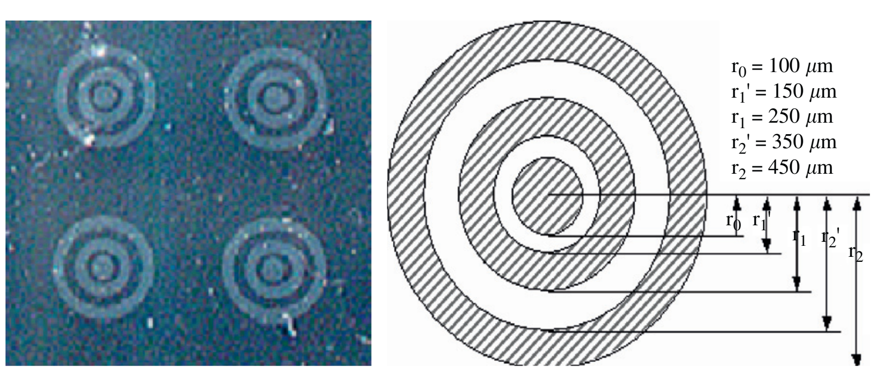

Fig. 1. (a) Surface photography of TiW electrodes and (b) the geometrical pattern for contact resistivity measurement of TiW/3C-SiC.