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Synthesis of silicon carbide films by combined implantation with sputtering techniques

Gaobao Li [a], Jizhong Zhang [a,b,c,*], Qingli Meng [a], Wenzhi Li [a,c]

[a] *Laboratory of Advanced Materials, Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, China*
[b] *International Centre for Materials Physics, Chinese Academy of Sciences, Shenyang 110016, China*
[c] *State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China*

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Abstract

Silicon carbide (SiC) films were synthesized by combined metal vapor vacuum arc (MEVVA) ion implantation with ion beam assisted deposition (IBAD) techniques. Carbon ions with 40 keV energy were implanted into Si(1 0 0) substrates at ion fluence of 5×10^{16} ions/cm^2. Then silicon and carbon atoms were co-sputtered on the Si(1 0 0) substrate surface, at the same time the samples underwent assistant Ar-ion irradiation at 20 keV energy. A group of samples with substrate temperatures ranging from 400 to 600 °C were used to analyze the effect of temperature on formation of the SiC film. Influence of the assistant Ar-ion irradiation was also investigated. The structure, morphology and mechanical properties of the deposited films were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM) and nanoindentation, respectively. The bond configurations were obtained from IR absorption and Raman spectroscopy. The experimental results indicate that microcrystalline SiC films were synthesized at 600 °C. The substrate temperature and assistant Ar-ion irradiation played a key role in the process. The assistant Ar-ion irradiation also helps increasing the nanohardness and bulk modulus of the SiC films. The best values of nanohardness and bulk modulus were 24.1 and 282.6 GPa, respectively.

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Keywords: Silicon carbide; MEVVA; IBAD; Ion implantation

1. Introduction

Thin SiC films have attractive properties, like a wide band gap, high electrical breakdown field, high saturated electron velocity, high thermal conductivity, good radiation resistance, high hardness and excellent physical and chemical stability at high temperature. These properties make silicon carbide thin films promising materials for application in electronic and optical devices, such as microwave power devices and high temperature sensor applications [1–3]. Consequently, the synthesis of SiC thin films has drawn worldwide attention in the last decades.

Many techniques have been used to synthesize thin SiC films, such as chemical vapor deposition (CVD) [4], molecular beam epitaxy (MBE) [5], ion beam mixing [6], ion implantation [7] and ion beam sputtering [8]. CVD is most widely used but requires high temperature [4,9]. It was suggested that SiC film should also be synthesized on Si substrates below 1000 °C for device integration [10]. Therefore, synthesis of crystalline SiC film at low substrate temperature needs to be developed.

The metal vapor vacuum arc (MEVVA) ion-source implanter was invented in the mid-1980s [11]. It has been used to prepare thin SiC layers by implanting carbon ions into Si substrates [7]. Ion implantation was also used to increase the adhesive strength between films and substrates. For instance, Yu et al. reported that a mixed layer between a Cu film and a Si substrate (created by implantation of Cu ions into the Si matrix) increased the adhesive strength [12]. Ion beam assisted deposition (IBAD) has been already used to deposit semiconductors, metals and oxide films. It has a good repeatability

* Corresponding author at: Laboratory of Advanced Materials, Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, China. Tel.: +86 10 6277 1809; fax: +86 10 6277 1160.
E-mail address: zjz@mail.tsinghua.edu.cn (J. Zhang).

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and provides precise control of the ion energy and current. This makes it a powerful technique.

In this work, synthesis of SiC thin films by combined metal vapor vacuum arc (MEVVA) ion-source implantation with ion beam assisted deposition (IBAD) is investigated. The Si substrates were pretreated with carbon ion implantation at ion fluence of 5×10^{16} ions/cm^2. The films were deposited by ion beam assisted deposition (IBAD) technique. In this way, SiC films with a high adhesive strength were obtained. A standard commercial MEVVA ion-source implanter and a IBAD system were combined in a single set-up that was used to accomplish the process. Therefore, after the Si substrates were pretreated by means of implantation, following deposition of carbon and silicon atoms can be carried out in situ to avoid exposing to the atmosphere. The experimental results show that microcrystalline SiC thin films were synthesized, at a substrate temperature of 600 °C, without post annealing.

2. Experimental

A N-type Si(1 0 0) wafer of 435 μm thickness with resistivity 5.5 Ω cm was used as substrate. The N-type wafer was cut in 5 different samples with size 10 mm × 10 mm. They were labelled A, B, C, D and E, respectively. Before loading into the vacuum chamber, the samples were ultrasonically degreased with acetone and alcohol and, then, rinsed with deionized water.

The combined MEVVA and IBAD system used for the films deposition is shown in Fig. 1. The vacuum chamber is pumped by a turbomolecular pump, assuring a base pressure better than 4×10^{-4} Pa. A pure silicon wafer and a graphite plate were used as silicon and carbon source, respectively. They were placed on two water-cooled sample holders, and sputtered with two low-energy Kaufman ion sources. A halogen lamp was used to heat the sample holder on which the silicon substrate was mounted. A thermocouple was used to measure the temperature.

Prior to deposition, three different steps were applied. First, the substrate was heated to a fixed temperature. Second, Ar ions with 20 keV energy were sent on the sample with an ion density of 20 μA /cm^2 for 10 min, using a medium-energy Kaufman ion source. This was to clean away the oxide and/or impurity species on the sample surface. Third, carbon ions at 40 keV energy were implanted into the sample at ion fluence of 5×10^{16} ions/cm^2 with an ion density of 10 μA/cm^2. Finally, silicon carbide films were deposited on the Si(1 0 0) samples by co-sputtering of silicon and carbon species. The ion beam energy was 2750 eV. The ion beam density was I (carbon) = 2.2 mA/cm^2 and I (silicon) = 4.4 mA/cm^2, respectively. Meanwhile, an Ar-ion beam with 20 keV energy was sent vertically on the samples with an ion density of 15 μA/cm^2 by a medium-energy Kaufman ion source.

Ion beam energy and current density were constant for all the samples. To analyze influence of the substrate temperature on the SiC films, the substrate temperature was fixed to 400, 500 and 600 °C, respectively. Samples with and without assistant Ar-ion irradiation were also prepared to analyze influence of the assistant Ar-ion irradiation. The growth conditions and thickness of all the samples have been summarized in Table 1.

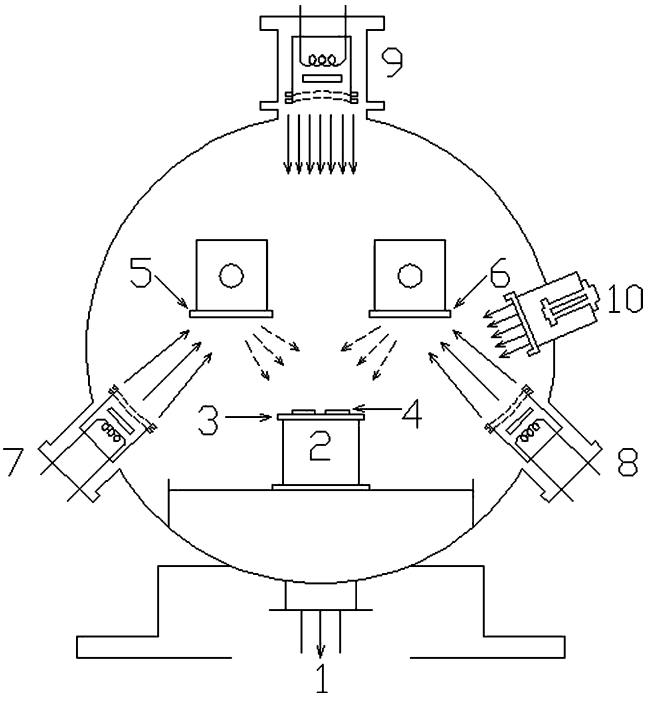

Fig. 1. Configuration of the MEVVA-IBAD device used in the work. (1) Molecular pumping; (2) heating system; (3) sample holder; (4) sample; (5) carbon target; (6) silicon target; (7) low-energy Kaufman ion source; (8) low-energy Kaufman ion source; (9) medium-energy Kaufman ion source; (10) MEVVA ion source.

Microstructure and composition of the deposited films were investigated with different methods. X-ray diffraction (XRD), D/max-RB, was employed to identify the films phase. IR absorption spectra were collected using a Nicolet 5700 IR absorption spectrometer. Raman spectra were recorded at room temperature using a RM 2000 Microscopic Confocal Raman Spectrometer. SEM, JSM-6460LV, was used to observe surface morphologies and cross-section images of the samples. XP nanoindenter, MTS, was employed to measure the nanohardness and bulk modulus of the deposited films.

3. Results and discussion

3.1. XRD analysis

Fig. 2(a) shows X-ray diffraction spectra (Cu Kα irradiation, λ = 1.5418 Å) collected for films A, B and C deposited at substrate temperature 400, 500 and 600 °C, respectively. It can be found in spectra for the samples A and B that a wide band beside the Si(2 0 0) peak (at $2\theta = 33.0^\circ$) can be identified to amorphous SiC [13]. As the substrate temperature increased to 600 °C, the spectrum for the sample C shows diffraction peaks typical of SiC microcrystalline structure. The peak centered at $2\theta = 35.4^\circ$ is coming from (1 1 1) of 3C–SiC or (1 0 2) of 6H–SiC, and the weak peak at $2\theta = 34.2^\circ$ is related to (1 0 1) of 6H–SiC [14]. Moreover, the peaks located at $2\theta = 44.9^\circ$ and 49.6°