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Full Length Article

Effects of rapid thermal annealing on the contact of tungsten/p-diamond

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ABSTRACT

The electrical properties, surface morphology and interface characteristics of W/p-diamond contact before and after annealing have been investigated. It is shown that the as-fabricated W/p-diamond contact exhibited non-linear behavior. After annealing at a temperature higher than 400 °C, the W/p-diamond contact showed ohmic behaviour. The specific contact resistance of W/p-diamond was $8.2 \times 10^{-4}\ \Omega\cdot cm^2$ after annealing at 500 °C for 3 min in a N_2 ambient, which was extracted from fitting the I-V relationship of TLM. It is noted that the RMS roughness increases with the annealing temperature increasing, which could be ascribed to the formation of WO_X by the reaction of W and oxygen at high temperature. The XPS measurement showed that the barrier height of the W/p-diamond is 0.45 ± 0.12 eV after annealing at 500 °C. Furthermore, the formation of defects at the W/p-diamond interface, probably created by the formation of tungsten carbide during rapid thermal annealing, should be responsible for the ohmic formation of W/p-diamond after annealing at high temperature.

1. Introduction

Diamond is a promising material for high frequency and high power electronic device applications due to its excellent properties, such as wide band gap (5.47 eV), high critical breakdown field (>10 MV/cm), high thermal conductivity ($22\ W\cdot cm^{-1}\cdot K^{-1}$), high carrier mobility ($\sim 3800\ cm^2\cdot V^{-1}\cdot s^{-1}$ for holes and $\sim 4500\ cm^2\cdot V^{-1}\cdot s^{-1}$ for electrons) and high saturation velocity ($10^7\ cm\cdot s^{-1}$) [1,2]. Although many factors of diamond power devices have been investigated, ohmic contact is still needed to be further studied to provide high current density and low-power consumption. For semiconducting diamond, there exist two main ways to fabricate low contact resistance ohmic contact, i.e., heavy doping and carbide formation. Many refractory metals such as Ti, Mo and Ta, which were capped by Au, were used as contact material for p-type diamond, showing ohmic properties on account of the formation of carbide at the interface after annealing temperature above 400 °C [3–5]. However, few investigations of tungsten (W) contact on p-type diamond were reported. It is well known that W has the highest melting point among metals and high thermal conductivity. Thus, it could be a good candidate for allowing the device work stably at high temperature. In addition, it also has the advantage of controllable carbide formation because carbides formed with diamond at elevated temperatures [6–8].

The purpose of the present study is to characterize W contacts on p-type diamond. Here, W was used as contact metal. We have investigated the detailed electrical, surface morphological and interface characteristics of W/p-diamond contacts before and after annealing. It is shown that the W/p-diamond contact can obtain the specific contact resistance (ρ_C) value and contact barrier height (ϕ_{BH}) as low as $8.2 \times 10^{-4}\ \Omega\cdot cm^2$ and 0.45 ± 0.12 eV after annealing at 500 °C for 3 min in nitrogen atmosphere, respectively.

2. Experiment

Boron doped ($10^{19}\cdot cm^{-3}$) Ⅱb-type high-pressure high-temperature diamond (p-diamond) substrate ($3.0 \times 3.0 \times 0.3\ mm^3$) was used in this experiment. The substrate was cleaned in acid solution ($HCl:HNO_3 = 3:1$ by volume) at 80 °C for 30 min to remove non-diamond impurities. Atomic force microscope (AFM) and X-ray diffraction (XRD) were carried out to evaluate the morphology and quality of the diamond. 40 nm thick Au film with an area of $700 \times 700\ \mu m^2$ was patterned on this diamond bottom right corner using photolithography and magnetron sputtering techniques. Same Au film was deposited on the molybdenum sample as reference. Thereafter, 150 nm thick W film was patterned on p-diamond surface to form Transmission Line Model (TLM) configurations with an area of $100 \times 150\ \mu m^2$ and gap spacing (d) of 5,

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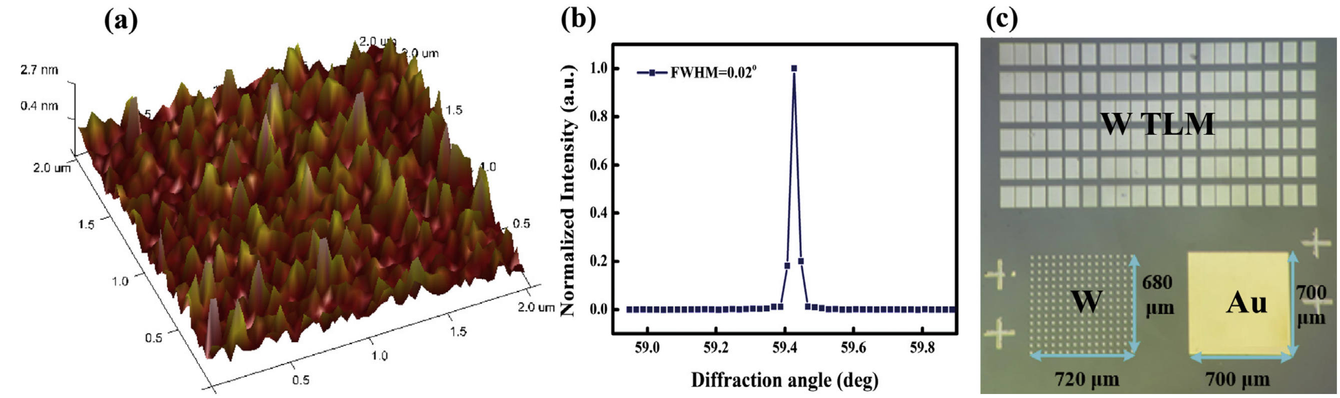

Fig. 1. (a) AFM image of the surface with an area of 2 × 2 μm^2, (b) XRD image of p-diamond, (c) OM image of full scale of diamond sample with TLM configurations, 20 × 20 μm^2 W electrodes and Au film.

10, 15, 20, 25, 30 μm, and also 20 × 20 μm^2 W electrodes with a total area about 720 × 680 μm^2. After that, the sample was subsequently subjected to rapid thermal annealing treatments, carried out in nitrogen (N_2) ambient with temperature ranging from 300 °C to 500 °C with a step of 100 °C for 3 min. After each annealing step, current-voltage (I-V) measurements were carried out to characterize the evolution of the W/p-diamond contact electrical properties with increasing the annealing temperature.

The I-V characteristics were measured by Agilent B1505 A parameter analyzer. The surface morphologies of W/p-diamond before and after annealing were characterized by AFM and field emission scanning electron microscope (SEM). A commercial X-ray photoelectron spectrometer (ESCALAB 250Xi) was used to investigate the ϕ_{BH} of W/p-diamond before and after annealing. The excitation source of the XPS was a monochromatic Al Kα line with the energy of 1486.6 eV and the X-ray spot size were 500 μm.

3. Result and discussion

The AFM image exhibited a smooth diamond surface with surface root-mean-square (RMS) roughness about 0.6 nm, as shown in Fig. 1(a). The XRD measurement result, in which the XRD rocking curve of (0 0 4) has a relatively low full-width-at-half-maximum (FWHM) of 0.02°, exhibits a good crystalline quality, as shown in Fig. 1(b). The optical micrograph (OM) image of sample with TLM configurations, 20 × 20 μm^2 W electrodes region and Au film are shown in Fig. 1(c). The patterns are neat, indicating a good fabrication process of tungsten. Additionally, this sample was subjected to ultrasonic cleaning during lift-off process, exhibiting pretty well adherence of W on diamond.

The I-V characteristics of the as-fabricated and annealed W/p-diamond contacts were measured between two adjacent W pads with a spacing of 5 μm for the TLM configuration are shown in Fig. 2. As-fabricated W/p-diamond contact exhibits non-linear I-V characteristics and the current were relatively small. After 300 °C annealing, the I-V curve changes a little and still remains nonlinear. When the annealing temperature was increased above 400 °C, I-V curve becomes linear indicating an obvious ohmic contact, which could be ascribed to that carriers can transport the barrier between W and diamond.

The typical I-V characteristics correspond to different spacing between adjacent pads at room temperature of TLM configurations for W contacts to p-diamond annealed at 500 °C in N_2 for 3 min were shown in Fig. 3(a). All of these I-V curves are linear, illustrating an ohmic contact. For the TLM measurement, the total resistance R (obtained by V/I) for rectangular geometry can be expressed [9],

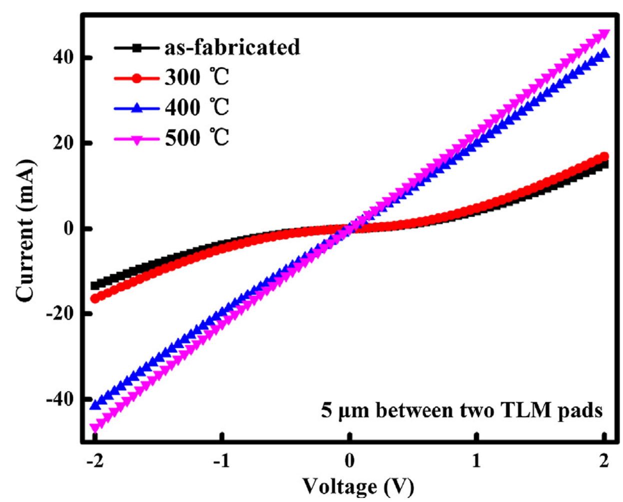

Fig. 2. I-V characteristics of as-fabricated and annealed W/p-diamond contact of TLM configurations.

$$R = \frac{2R_S L_T}{Z} + \frac{R_S}{Z} d \quad (1)$$

$$\rho_C = R_S L_T^2 \quad (2)$$

In which R_S denotes the sheet resistance of p-type diamond, L_T is the transfer length, and Z is the width of contact pad. When R was plotted as a linear function of d, R_S and L_T were extracted from the fitting curve. Then ρ_C can be calculated according to Eq. (2). In Fig. 3(a), the I-V measurements were exhibited as functions of space between two adjacent pads of TLM pattern. It is clearly seen that the W/p-diamond contact makes a linear I-V characteristic, and the R between any two adjacent contact pads could be deduced. The total resistance R between the pairs of contacts versus the contact spacing d for W/p-diamond annealed at 500 °C shown in Fig. 3(b) and the ρ_C value was calculated to be 8.2 × 10^{-4} Ω·cm^2 according to Eq. (2). The ρ_C vaule is comparable to C. M. Zhen's reports, in which the ρ_C value of Au/p-diamond ohmic contacts is 5.43 × 10^{-4} Ω·cm^2 after annealing at 500 °C in a vacuum of ~10^{-4} Pa [10].

The surface morphologies of W/p-diamond as fabricated, annealing at 300 °C and 500 °C for 3 min in a N_2 ambient are shown in Fig. 4(a–c), respectively. The surface RMS roughness of the as-fabricated W/p-diamond is quite smooth with roughness of 2.1 nm, as shown in Fig. 4(a). When the annealing temperature is set to be 300 °C, the surface RMS roughness of the annealed