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Single crystal diamond cantilever for micro-electromechanical systems

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ABSTRACT

A single crystal diamond (SCD) cantilever has been fabricated on HPHT diamond substrate by using ion implantation and patterning technique. Firstly, the carbon ions were vertically implanted into diamond substrate to create a non-diamond layer. Secondly, the diamond substrate was treated with photolithography and metal evaporation techniques to fabricate the desired cantilever pattern. Thirdly, a dry etching technique was used to selectively remove the defined regions. Then an electrochemical etching method was used to etch off non-diamond layer from the substrate. Furthermore, the mechanical properties of the suspended SCD cantilever have been investigated by atomic force microscopy. A Young's modulus of 907 GPa was estimated using the beam bending theory. At the final stage, an electrostatic actuator of SCD cantilever as a vertical switch device was realized.

1. Introduction

Diamond has many outstanding properties such as wide band gap, highest thermal conductivity, high breakdown field, high electron and hole mobility [1], high Young's modulus, low Poisson's ratio [2] and high corrosion resistance in hazardous chemical environment [3]. Due to its excellent properties in the aforementioned aspects, diamond has potential applications in high performance micro-electromechanical systems (MEMS). And the MEMS have become an important mainstream technology for a wide range of applications in chemical, biological, mass sensors, actuators, radio-frequency, resonator and many others [4–9]. Despite its potential applications, the fabrication of diamond micro-structure remains challenging. For instance, in actuators and radio-frequency MEMS, the micro-machining of three-dimensional structures in bulk diamond is technologically difficult. Previous works reported the use of such methods to produce scanning probe tips [10], cantilevers [11], field emitter [12], nano-electromechanical systems (NEMS) [13] and micro-fluidic channels [14]. However, the reported diamond MEMS are mainly fabricated on polycrystalline or nanocrystalline films because it is very difficult to grow SCD films on the hetero-substrates. Compared to SCD, polycrystalline or nanocrystalline diamond have the disadvantages of the existence of grain boundaries, impurities and large stress in the films, which causes difficulties in electrical conductivity control, poor optical transparency and less reproducible mechanical properties [15,16]. Therefore, MEMS made from these diamonds suffered from degradation in performance and poor reproducibility. To overcome the above-mentioned drawbacks and achieve the better performance, SCD is the choice for such applications. Parikh et al. developed a method for removing entire sheets of SCD from bulk samples based on ion implantation and acid etching or heating in oxygen methods [17]. In the next year, Marchywka et al. reported the use of electrochemical etching for lifting off application [18]. Then the utilization of ion implantation and lift-off technique has gained popularity for fabrication of free-standing SCD film [19–22], membrane windows [23] and micro-structures like microdisk, bridge and cantilever [24–28].

In this paper, a fabrication of SCD cantilevers by using ion implantation, inductively coupled plasma (ICP) etching and electrochemical etching techniques has been carried out. The mechanical properties of SCD cantilever have been investigated by atomic force microscopy (AFM), and its Young's modulus is then estimated from the beam theory formulation. Furthermore, its vertical switch behavior has also been discussed.

2. Experimental procedure

In our experiment, a polished HPHT Ib (001) SCD substrate with a dimension of $3 \times 3 \times 0.3$ mm^3 was used. Before ion implantation treatment, the substrate was subjected to a series of chemical cleaning processes [29] and coated with aluminum mask. Then, the substrate was selectively implanted by carbon ions with energy of 3 MeV at a dose of 2×10^{16} cm^{-2}. The stopping and range of ions were calculated by the "Transport of Ions in Matter" abbreviated as TRIM in Monte Carlo simulation code [30]. The ion implanted range will then serve as the non-diamond layer [17]. After ion implantation treatment, the substrate

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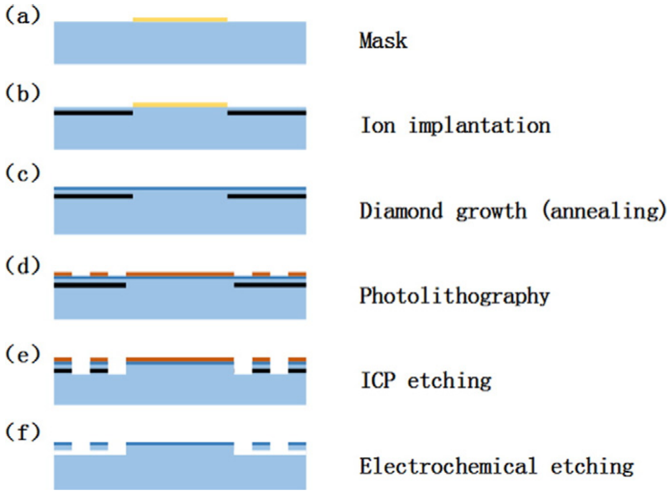

Fig. 1. Schematic of fabrication process of suspended SCD (a) Aluminum mask formation. (b) Ion implantation. (c) Growth and annealing by microwave plasma CVD system. (d) Aluminum mask fabrication. (e) ICP etching and (f) electrochemical etching.

was loaded into MPCVD chamber to grow SCD film. During growth, H_2 (500 sccm, 6 N), CH_4 (50 sccm, 6 N) and N_2 (0.5 sccm, 6 N) were used as the reaction gases. The chamber pressure, microwave power and substrate temperature were 16 kPa, 5 kW and 1175 °C, respectively. A thickness of 300 nm was achieved in total growth time of 6 h. The growth of SCD over the implanted substrate also serves to anneal the implanted range, providing a more reproducible non-diamond layer for subsequent processing [17,27]. A 1 μm thick aluminum film was formed by magnetron sputtering system to serve as a mask, then the pattern was transferred into diamond through ICP etching under the following process conditions: 50 sccm of O_2, 20 sccm of Ar, 10 mTorr of chamber pressure, and 800 W of power. The bias voltage was varied between 270 and 290 V. Sample was etched under these conditions for 20 min. An electrochemical etching system was used to treat the sample according to the procedure in Ref. [31] in which an alternating-current power supply with a maximum voltage of 2000 V, a neutral solution with low electrical conductivity and the electrodes with chemical stability were used. Finally, tungsten was deposited as electrodes for electrical measurements. The schematic of the fabrication process is summarized in Fig. 1.

After the fabrication of cantilevers, surface morphologies were characterized by optical microscopy (OM) and scanning electron microscope (SEM). The crystal qualities were investigated by Raman system with a 100× objective lens and laser with a wavelength of 532 nm. The displacement of SCD cantilever under different loading conditions of the AFM was used to determine its mechanical properties.

3. Results

Fig. 2 shows the color variation images of the substrate before and after ion implantation treatment. Fig. 2(a) indicates a normal transparent diamond substrate before treatment. Fig. 2(b) shows that the ion implantation treatment areas were turned into opaque. Fig. 2(c) shows the ion-induced TRIM of the damage density profile in diamond by C^+ ions implantation with energy 3 MeV.

Fig. 3(a) shows the cross sectional SEM image of as-grown diamond sample, which presents several layers with neat boundaries. The morphologies of as-grown diamond layer, surface diamond layer, non-diamond layer, and non-implantation diamond layer are labeled A, B, C and D, respectively. Fig. 3(b) illustrates the Raman spectra taken from four points in A, B, C, and D areas.

Fig. 4(a) shows the schematic of electrochemical etching system. Fig. 4(b)–(e) shows the color variation images of the sample during electrochemical etching. Fig. 5(a) and (b) displays the cross sectional SEM image of the sample before electrochemical etching. After electrochemical etching, the sample exhibits an obvious gap between the surface diamond layer and non-implantation diamond layer as shown in Fig. 5(c). The buried graphite layer provides the sacrificial layer for the formation of SCD cantilever structures. The sample morphologies were investigated by OM and AFM, as shown in Fig. 6. Fig. 6(a) exhibits the OM image of SCD cantilever sample. Fig. 6(b) indicates the AFM image of ICP etched area.

Fig. 7 shows the force-displacement (F–d) curve from AFM measurement obtained under different loading conditions on SCD cantilever. Fig. 8 exhibits the length^3-displacement (L^3–d) curve response of cantilever at a constant applied force. Fig. 9(a) shows the SEM image of sample coated with tungsten, and Fig. 9(b) demonstrates a sharp switching ON and OFF behavior. The details are explained in the subsequent section.

4. Discussion

We have obtained SCD cantilever through ion implantation, ICP and electrochemical etching techniques which will be presented in more detail in this section. Fig. 2(a) and (b) show color variation images of the substrate before and after ion implantation treatment. During ion implantation, a normal transparent diamond substrate was turned into opaque which is attributed to the formation of non-diamond layer in the patterned diamond areas. Fig. 2(c) shows the ion-induced damage density profile, the TRIM simulations suggest that these conditions should produce an implanting range of approximately 350 nm, and the average stopping is 1.62 μm. The distance from the non-diamond layer to the diamond surface is determined by the initial energy of the ion beam.

The cross sectional SEM image of as-grown diamond sample is shown in Fig. 3(a). The non-diamond layer C can be clearly observed, whose average thickness is about 384 nm, and the distance from

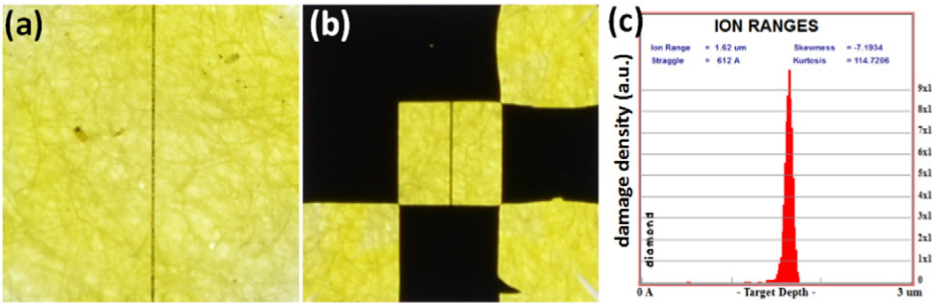

Fig. 2. Color variation images before (a) and after (b) ion implantation treatment. (c) TRIM Monte Carlo simulation of the damage density profile induced in diamond by C^+ ions of energy 3 MeV compared with the thickness of the free standing layer evaluated with interferometry measurements.