Single-crystal Diamond MEMS for Extreme Sensors

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Abstract

Diamond has been a potential rival of Si for MEMS in terms of the outstanding mechanical, electrical, thermal and chemical properties. These extreme properties not only enable developing highly reliable MEMS devices but innovating the sensitivity, precision, and stability. Here, we show the advanced research on single-crystal diamond (SCD) MEMS achieved in our lab. These include the invention of the smart-cut technology for fabricating SCD MEMS structures, energy dissipation mechanisms, and sensing/switch applications.

Keywords: Diamond, MEMS, Sensors

Introduction

The semiconductor electronics technology has witnessed the expansion from conventional silicon material to wide bandgap semiconductors such as GaN and SiC, and then to ultra-wide bandgap semiconductor such as AlN, BN, Ga_2O_3 and diamond. Similarly, MEMS has been experiencing the same development trend from silicon to diamond. In both fields, silicon semiconductor is still the mainstream. While silicon MEMS has been growing explosively thanks to the maturity in CMOS technology. MEMS based on the emerging wide-bandgap semiconductors is still at the initial stage.

Diamond is traditionally known for the highest mechanical hardness and Young's modulus for mechanical tools. It has also been realized that diamond exhibits outstanding semiconducting properties super to the existing semiconductor materials due to the ultra-wide bandgap energy, high carriers mobilities, high blocking voltages and the highest thermal conductivity[1]. In addition to these well documented mechanical and electronic properties, the known dopants in diamond have deep energy levels, greatly reducing the energy loss from electron-phonon interaction[2]. The non-existence of native oxides further mitigates the surface energy loss. Therefore, high resonance frequency and high quality (Q) factor diamond MEMS resonators can be achieved, enabling the development of MEMS sensors breaking the limits of silicon MEMS.

Nevertheless, the mechanical hardness and chemical inertness make micromachining diamond difficult. In this work, we present the single-crystal diamond (SCD) MEMS starting from the material micromachining and MEMS physis to sensing applications developed in our lab.

Micromachining of single-crystal diamond

At this stage, it is still difficult to deposit high-quality SCD epilayers on foreign substrates (Si etc). Therefore, Silicon based MEMS micromachining process is not applicable for SCD. Uniquely, the allotropes of carbon offer the route to transform sp3-hybridized crystal diamond to sp2-hybridized graphite-like carbon. This feature forms the basis for the fabrication of SCD MEMS structures, which has been called as the smart-cut method. The strategy here is to use high-energy ion implantation into a SCD substrate, which leads to the formation of buried graphite-like carbon within the SCD substrate[3]. By using lithography and etching process, the SCD MEMS structures can be released. This method enables the mass production of SCD MEMS with well controlled dimensions and internal stress. The fabrication process is briefly illustrated in Fig.1(a). Fig.1(b) shows the optical images of SCD MEMS cantilevers produced by the smart-cut method.

Energy dissipation and quality factors of SCD MEMS

The energy dissipation determines the quality (Q) factor of a MEMS resonator, which, in turn, influences the ultimate device performance, such as the sensitivity, precision, frequency stability, and the noise level of the devices. The energy dissipations in diamond MEMS resonators include both intrinsic and extrinsic loss. The overall Q factor can be generally written as

$$\frac{1}{Q}=\frac{1}{Q_{air}}+\frac{1}{Q_{clamp}}+\frac{1}{Q_{TED}}+\frac{1}{Q_{MD}}+\frac{1}{Q_{surface}} \quad (1)$$

where Q_{air}, Q_{clamp}, Q_{TED}, Q_{MD}, and $Q_{surface}$ represents the dissipation sources from air damping, clamping loss, thermoelastic damping (TED), mechanical defects (MD), and surface loss, respectively. The extrinsic loss Q_{air} and Q_{clamp}, can be reduced by changing the measurement environments, such as in vacuum to avoid air damping, optimizing the device geometry to reduce the clamping loss, etc. The material properties and crystal quality define the intrinsic loss. The materials properties such as the thermal conductivity, thermal expansion coefficient affect the Q_{TED}. Reducing the crystal defects such as the grain boundaries, dislocations, and impurities are important to improve the Q factor. In SCD MEMS structures fabricated by the smart-cut method, ion-implantation induced point defects degrade the Q factor. Therefore, the Q factor in such a case is at the order of 1, 000. The strategies to reduce the effect of these defects include increasing the SCD epilayer thickness, high-temperature annealing, and removing the damaged layer in the MEMS structures. Increasing the epilayer thickness is the simplest way, which can increase the Q factor by over 10 times[4]. However, increasing the thickness also increases the damping loss, limiting the Q factors. By annealing the SCD MEMS structure in an ultra-high vacuum at high temperatures over 900°C, the Q factor was improved by twice[5]. These two methods can not totally remove the damaged layer, the Q factor is still at the order of 10,000. The most efficient way is the combination of the growth of a high quality SCD epilayer and the removal the damaged layer. Eventually, the Q factor over 1 million was achieved at room temperature (Fig. 2) for the smart-cut method fabricated SCD cantilevers[6], which is the same level as that of the SCD cantilever by thinning a SCD plate bonded with a foreign substrate.

Extreme SCD MEMS sensors

The SCD MEMS showed excellent thermal stability up to 1000 K and low thermal coefficient of resonance frequency (TCF) ~ 5ppm, much less than those of Si and III-nitrides. The high thermal stability enables the development high-temperature and high-reliability MEMS sensors and switches.

We developed all-electrical SCD MEMS magnetic sensors able to work up to 773 K[7]. In this magnetic sensor, a high-Curie temperature magnetostrictive FeGa thin film (~ 80 nm) was deposited on the SCD cantilevers beams (Fig.3). To enhance the adhesion between diamond and FeGa, a thin Ti layer was deposited. When applying an external magnetic field on the SCD cantilever beam, the force induced by the magnetostrictive FeGa film is transferred to the beam, inducing the shift of the resonance frequency of the cantilever (Fig.3b and Fig.3d). This is something equal to the change of the Young's modulus (E). Therefore, this physical principle is also called ΔE effect. The FeGa/Ti/SCD MEMS structure allows the device sensing magnetic field up to 773K at least. The noise level of the device remained as low as 10 nT/Hz$^{0.5}$ even at 773K.

Due to the high sensitivity of MEMS for mass sensing. The surface states information of a semiconductor can be revealed in an alternative way from the conventional ways such as X-ray photoelectron spectroscopy. Oxygen-terminated diamond surface is commonly utilized and vital for semiconductor diamond electronic devices such as Schottky diodes, photodiodes, and metal-oxide-field effect transistor (MOSFETs). By annealing the SCD cantilevers in an ultra-high vacuum, we measured the resonance frequency shift, based on which the mass loss (~pg) and thickness (~nm) of the surface absorbents of the surface terminations were disclosed[8].

By using the robust mechanical hardness and wear resistance, diamond nanomechanical system (NEMS) switch was developed, as shown in Fig. 4. The structure of the NEMS switch resembles a transistor, having source, drain and gate electrodes. Since the off-current is nearly zero, the subthreshold swing is nearly zero, overcoming the thermodynamic limit (60mV/dec) of a field-effect transistor. Therefore, the standby power consumption of the SCD NEMS switch is nearly zero. The diamond NEMS can also operate at high temperatures [3].

Conclusion

We developed the smart-cut method for the mass fabrication of SCD MEMS structures. This process is highly controllable and controllable. The Q factor the resulting SCD MEMS cantilever beam was over 1 million at room temperature. The SCD MEMS was used for various applications such as high-reliability high-temperature MEMS magnetic sensors, surface state analysis of a semiconductor and NEMS switch. Diamond MEMS paves the way for innovating the conventional MEMS in either performance and sensitivity.

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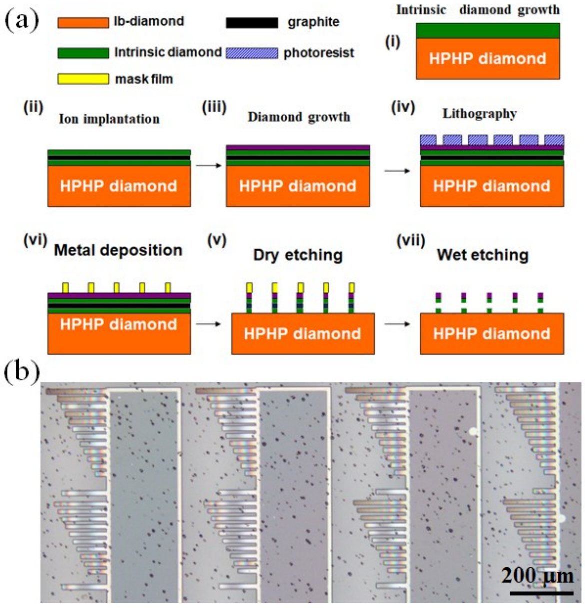

Fig. 1:(a) Fabrication of SCD MEM strucures (i) diamond growth, (ii) ion implantation, (iii) diamond growth, (iv)-(vii) phototography and structrures release. (b) Opticla image of SCD cantiever beams.

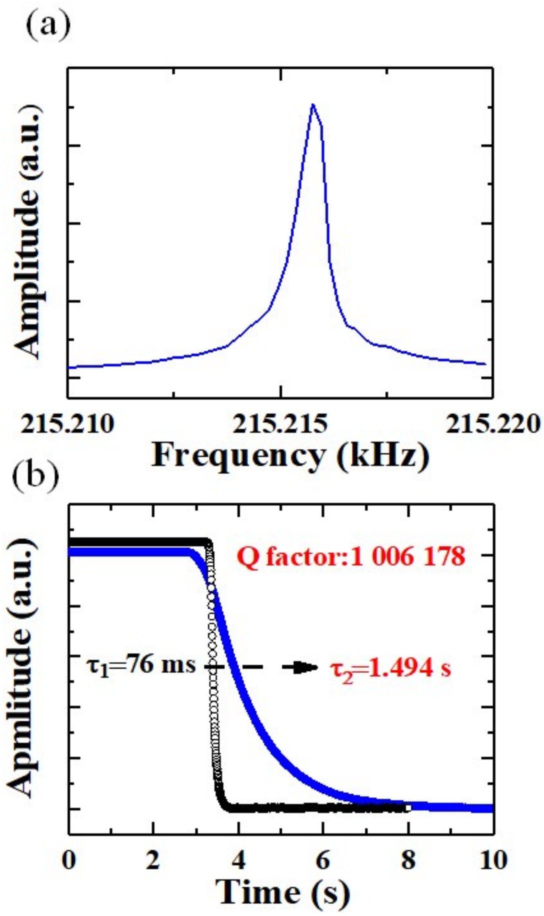

Fig. 2: (a) resonance frequecy spectra of a 140 μm long SCD cantilever (b) ring-down measurents of the cantilever before and after removing the damaged layer.

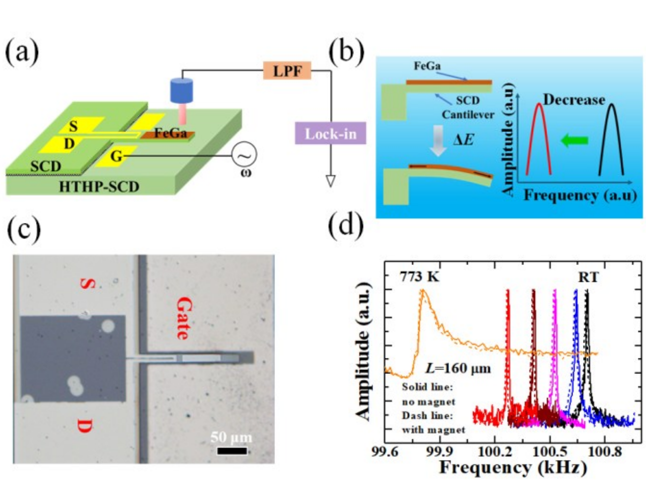

Fig 3: On-chip diamond MEMS magnetic sensor. (a) all-electrical actuation and readout scheme, (b) physics principle for magnetic sensing, (c) optical image of the FeGa/Ti/diamond on-chip MEMS magnetic sensor, (d) magnetic sensing up to 773 K.

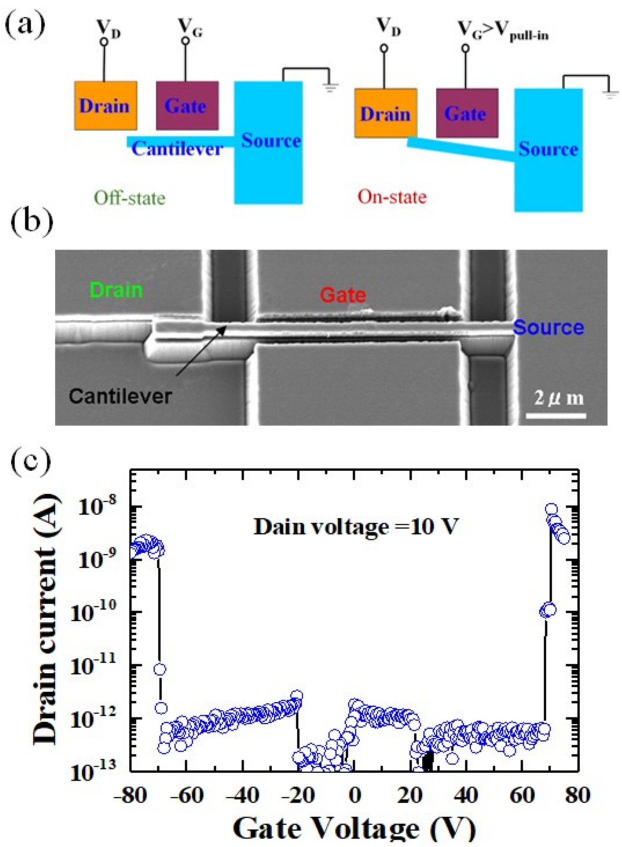

Fig.4: Diamond NEMS switch (a) switching principle: the gate voltage inducing the deflection of the beam to connect the source and drain, (b) optical image of a SCD NEMS switch (c) Electrical switching proeprties.