Fabrication of Micro-oscillator by Printing technologies of Au thin film and graphene oxide

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Abstract:
This present study is intended to show some test results of fabrication of micro-oscillators by transfer-printing (TP) of Au thin film and inkjet printing of graphene oxide (GO) nanoparticles. Au thin film is formed into a double-supported micro-beam to function as a micro-oscillator on a polymer substrate. Au thin film is also fabricated on a pre-coated Au substrate by atomic diffusion bonding assisted transfer-printing. This micro-oscillator can be driven by electrostatic force with 90 – 210 V of applied voltage and less than 10 kHz. The resonance frequency is 0.28 kHz. GO nanoparticles are deposited on the transfer-printed Au thin film by inkjet printing. The laminated thin film of Au and GO nanoparticles has higher modulus than that of Au thin film.

Keywords: Surface and tribology, transfer-printing, Au thin film, inkjet printing, graphene oxide, oscillator

1. Introduction

This present study describes micro-oscillators fabricated transfer-printing (TP) and inkjet printing. A micro-oscillator is used for resonant MEMS acceleration and gas sensors, as its resonance frequency shifts due to external forces and mass changes with adsorbents. The micro-oscillator, three-dimensional mechanical structure, is generally fabricated by semiconductor processes including sacrificial layer etching. Although the semiconductor process is very sophisticated, it involves complicated procedures and high cost. Meanwhile, printing technologies such as offset printing, inkjet printing, nanoimprint, transfer-printing becomes a great candidate for simplified, on-demand, and low-cost micro fabrication for micro-electronic and MEMS devices.

Transfer-printing (TP) transfers a thin film from a stamp onto a substrate to make a micro-pattern [1 – 3]. It was demonstrated that Au thin film was formed in double-supported micro-beams by transfer-printing on a pre-structured (grooved) substrate [4]. Atomic diffusion bonding assisted transfer-printing (ADA-TP) is effective to enhance adhesiveness between Au thin film and substrate [11]. It is reasonable to make a micro-oscillator by a technique based on transfer-printing. A micro-beam fabricated by transfer-printing, however, has not been actuated and operated as the oscillator.

Au and Cu thin film, typical transfer-printed material, have low Young's modulus as compared to Si and SiO_2. As the sensitivity of resonant sensors depends on Young's modulus, a lamination of these metal thin film and high-modulus material is effective for the micro-oscillator. Graphene oxide (GO) is an important candidate material. GO has high Young's modulus above 700 GPa [5, 6]. Two-dimensional nanoparticles of GO are commercially available. As hydrophilic GO nanoparticles can disperse in water and ethanol, so that they can be deposited by wet processes such as spin coating, dip coating, and inkjet printing [7, 8]. Inkjet printing enables to deposit GO nanoparticles onto a transfer-printed thin film.

The purpose of this study is to intend to show some results about fabrications of micro-oscillators of Au and Au/GO-laminated thin film by transfer-printing and inkjet printing, and also basic vibration characteristics of the micro-oscillator driven by electrostatic force.

2. Experimental methods

2.1 Fabrication of Au/GO micro-oscillator

Figure 1 and 2 shows a procedure of fabrication of Au and Au/GO micro-oscillators and set-ups of transfer-printing and inkjet printing, respectively. A photoresist (RD1225, SHOWA DENKO) was deposited on an ITO/glass substrate and was formed in micro-grooves with a width of 250 μm or 300 μm by laser lithography (μPG101, HEIDELBERG). The ITO film functions as a bottom electrode for electrostatic drive of micro-oscillator. In the case of ADA-TP, the substrate was processed with UV/O_3 and was coated with Au thin film (30 nm). The coated Au thin film would be strongly bonded to subsequently transfer-printed Au thin film.

A micro-ridged stamp with 150 μm width was formed by high modulus poly-dimethyl-siloxane, h-PDMS (VDT-731, Gelest), for transfer-printing. Au thin film with 300 nm in thickness was deposited by vacuum vapor deposition (MPVAP, MICROPHASE) and ECR sputtering (EIS-200ER, ELIONIX).

The transfer-printing process is as follows. The stamp with Au thin film was contacted to the photoresist surface of substrate. The contact pressure was 0.75 MPa for the substrate with 250-μm-wide grooves, and 2.4 MPa for the substrate with 300-μm-wide grooves. The substrate temperature and contact time were 150 °C and 10 minutes, respectively. The Au thin film was transferred from the stamp onto the substrate after releasing the stamp.

The atomic diffusion bonding assisted transfer-printing (ADA-TP) is as follows. The stamp was contacted to the Au-coated substrate with contact pressure 0.7 MPa and temperature 150 °C for 5 minutes. Since Au has almost same surface energy as diffusion activation energy, Au atoms can inter-diffuse between two thin films to make strong bonding [9 – 11].

In the case of Au/GO-laminated film, GO nanoparticles (G-21S, EMJapan) were deposited on Au thin film by inkjet printing system (IJK-200H, MICROJET). GO suspension is an aqueous solvent with a concentration of 0.05 wt%. The authors found appropriate inkjet conditions to drop GO suspension. The droplet of GO suspension were placed on the Au thin film (micro-oscillator) by a controlled X-Y stage and in-situ observation of digital microscope.

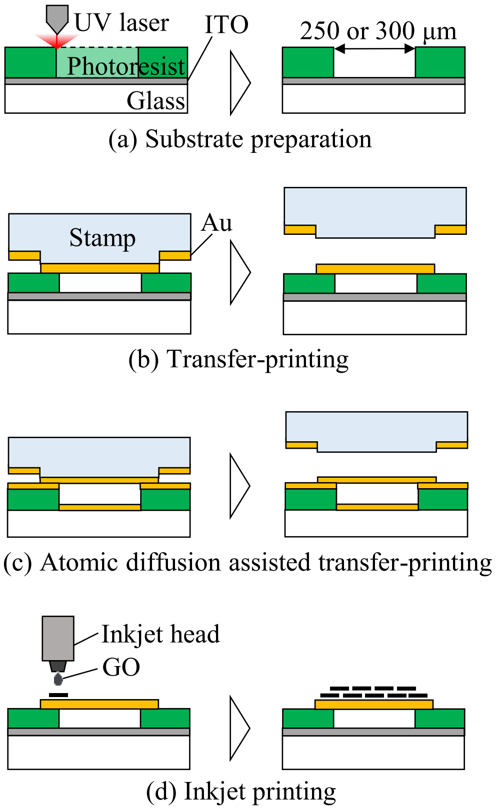


Figure 1: Fabrication process of micro-oscillator.

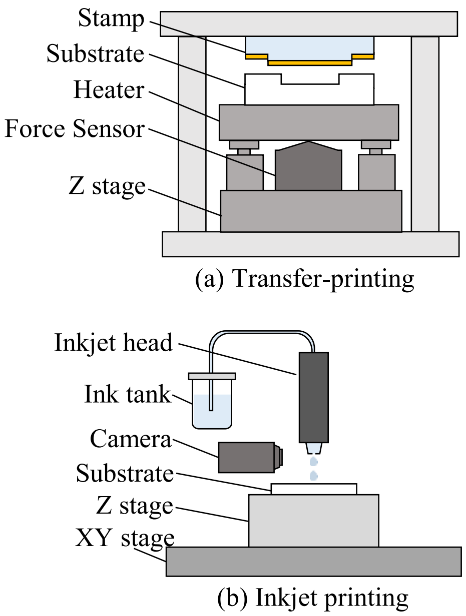


Figure 2: Experimental set-up.

2.2 Electrostatic drive of micro-oscillator

Figure 3 shows a set-up of electrostatic drive and displacement measurement system. The fabricated micro-oscillator and the bottom electrode (ITO) were connected to a power, a function generator (WF1945B, nf corp.) and an amplifier (M-2654, mess-tek). The center displacement of the micro-oscillator was measured by a laser displacement meter (CL-PT010, KEYENCE) with φ3.5 μm of spot diameter. The static displacement was measured by applying DC voltage (90 – 210 V). To confirm the effect of GO, it was compared that displacement of Au and Au/GO micro-oscillator when DC voltage was applied. The damping ratio of Au micro-oscillator and frequency responses of two oscillators were investigated. An impulse voltage (180 V, 2 ms) was applied to the micro-oscillator to obtain the damping ratio. Meanwhile, AC voltage ($V_{p\text{-}p}$ = 150 V, f = 0.1 – 11 kHz) was applied.

The vibration characteristics of the micro-oscillator were also analyzed using finite element method (COMSOL Multiphysics, KESCO). A resonance frequency of Au micro-oscillator was analyzed by the FEM analysis. The mechanical properties of Au thin film were also estimated by same method.

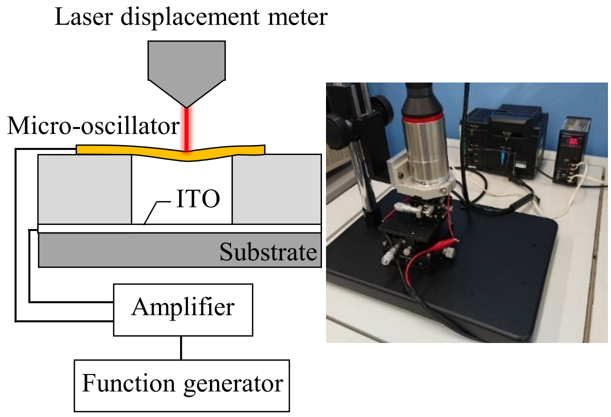


Figure 3: Set up of electrostatic drive.

3. Result of fabrication of micro-oscillator

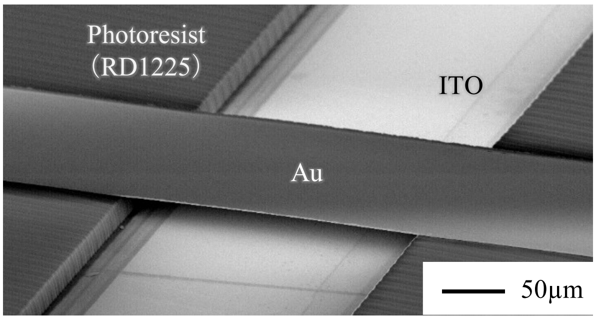
Figure 4 shows SEM images of micro-oscillators fabricated by TP and ADA-TP. Both Au thin films were transfer-printed on the polymer or the Au-coated substrate, which formed in a double-supported micro-beam of micro-oscillator. Although the Au thin film was slightly bent downward by about 80 nm, it was considered that these micro-beams could be used as oscillators.

Figure 5 shows optical microscope images of Au micro-oscillator before and after inkjet printing of GO nanoparticles. The GO nanoparticles were successfully deposited on the top face of the Au micro-oscillator, as the top surface turned black or dark brown and it was confirmed that GO nanoparticles were laminated on the Au thin film surface. Elemental analysis using EDX also shows GO deposition.

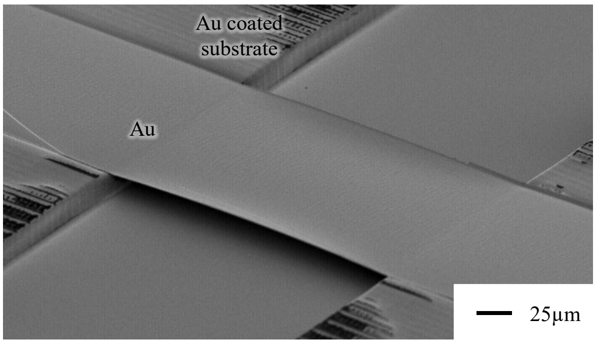
4. Result of electrostatic drive

4.1. Evaluation of mechanical strength

It was confirmed that the Au micro-oscillator could be deflected by electrostatic force with applied voltage. Figure 6

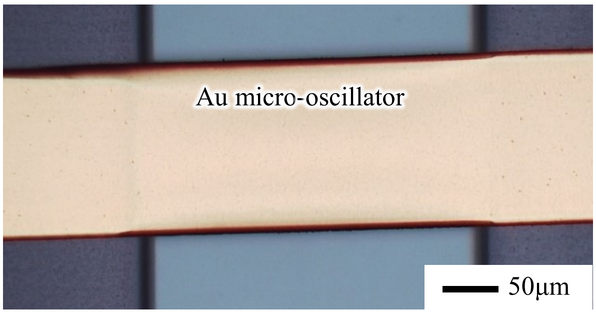


(a) Fabricated by transfer-printing

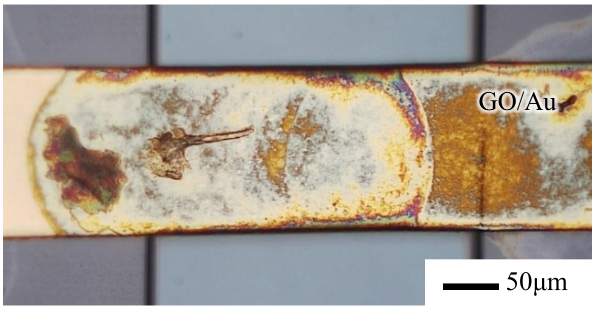


(b) Fabricated by atomic diffusion assisted transfer-printing

Figure 4: Au micro-oscillator.



(a) Before inkjet printing



(b) After inkjet printing

Figure 5: Graphene oxide film formation on Au micro-oscillator.

shows typical static displacement of the micro-oscillator (250-µm-long micro-beam) applied with DC voltage. The displacement means maximum deflection at the center of the micro-oscillator. The displacement proportional increased with applied voltage in the range of 90 to 180 V. The maximum displacement reached over 400 nm at 180 V.

Figure 7 shows an example of FEM analysis of the micro-oscillator. The Young's modulus of the transfer-printed Au thin film was estimated by comparing the experimental result (Fig. 6) to the FEM (Fig. 7). The Young's modulus of the Au thin film is estimated to be about 40 GPa, while Au bulk is generally 78 GPa. It is reasonable that thin film of material has lower modulus than that of bulk materials. Previous studies have also investigated Young's modulus of Au thin film [12 – 14]. The modulus of Au thin film can be improved by appropriate conditions of vapor or sputter deposition as well as by the lamination of GO nanoparticles.

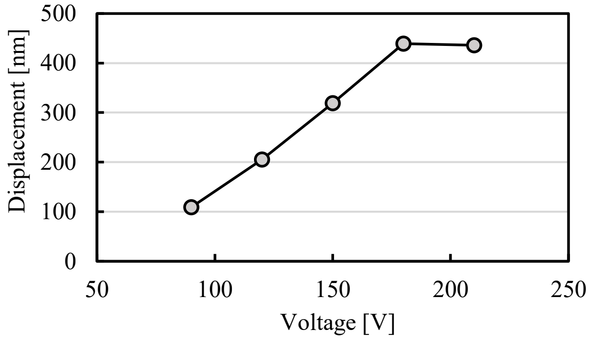


Figure 6: Relationship between displacement and voltage.

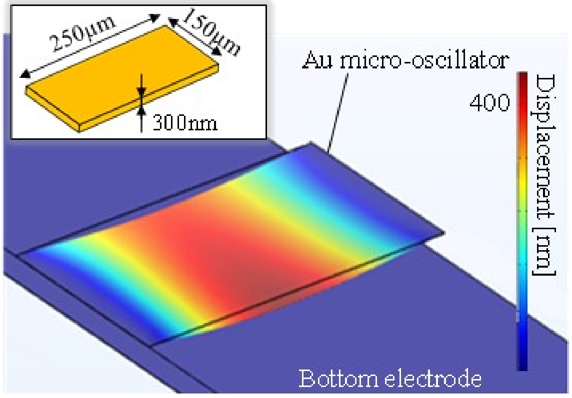


Figure 7: Result of FEM analysis (Applied 180 V).

4.2. Au/GO micro-oscillator

Figure 8 shows the relationship between applied voltage and displacement of Au/GO micro-oscillator. The sample of Au micro-oscillator (300-µm-long micro-beam) was different from that of Fig. 6, while it was the same as the base of Au/GO micro-oscillator. The sample of the micro-oscillator used in Fig. 6 were 250 µm in length, but these samples of the micro-oscillator were 300 µm in length. Both displacement of Au and Au/GO micro-oscillators increased with applied voltage. The displacement of Au/GO micro-oscillator was about 0.7 times that of the Au micro-oscillator. This results clearly shows that the lamination of GO nanoparticles increases the Young's modulus of Au thin film. It was considered that residual stress in Au thin film might be larger than that of Fig. 6.

4.3. Vibration characteristics of Au micro-oscillator

Figure. 9 shows an impulse response with applied voltage. The displacement (deflection) gradually decreased with time.

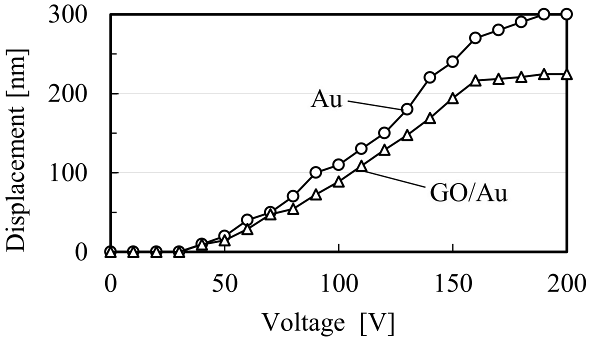


Figure 8: Displacement of micro-oscillator with applied voltage.

As the damping ratio was estimated to be 0.17. It indicated the micro-oscillator could resonate. The resonance frequency was estimated to be 0.3 kHz because of the interval of peaks 3.2 ms.

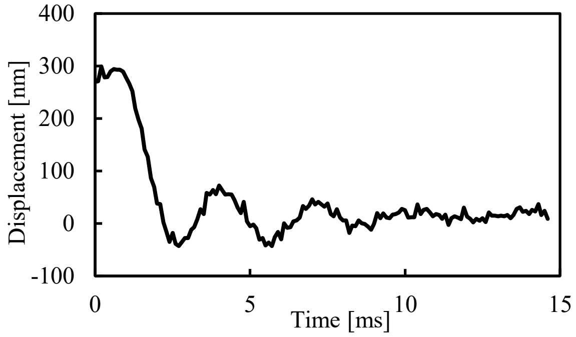
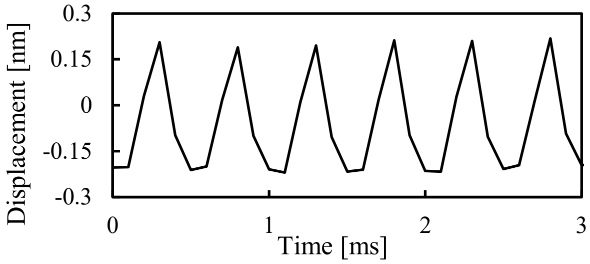
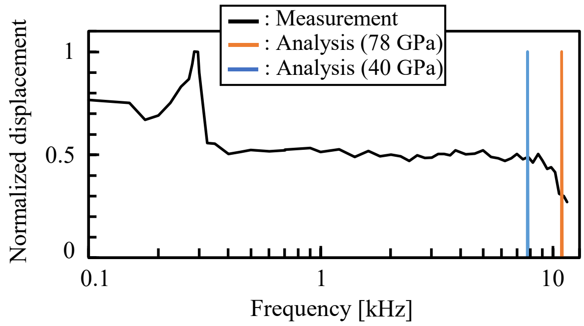


Figure 9: Response to the impulse voltage of Au micro-oscillator.

Figure 10 (a) shows typical displacement of the Au micro-oscillator when cyclic voltage (2 kHz) was applied. It was demonstrated that the micro-oscillator could be dynamically deflected. The period of oscillation was 0.5 ms, so that the frequency of oscillation was corresponded to that of applied voltage. Figure 10 (b) shows the relationship between the frequency of applied voltage and displacement of the micro-oscillator. It was confirmed that Au micro-oscillator could be operated in the range of 0.1 kHz and 10 kHz. The maximum displacement, clear peak, was found at 0.28 kHz, so that it was considered to be a resonance frequency. This resonance frequency was almost consistent with the result estimated from the impulse response shown in Fig. 9. The resonance frequency estimated by FEM analysis, however, was 10.9 kHz in the case of modulus of 78 GPa and 7.8 kHz of modulus of 40GPa. It is considered that this difference in resonance frequency is attributed to be internal defects in the micro-oscillator as well as material properties (Young's modulus). One of the internal defects was caused by low adhesion strength between the transfer-printed Au thin film and the substrate. It is expected that the resonance frequency of the micro-oscillator fabricated by ADA-TP is close to the theoretical value, although it has not been tested for electrostatic oscillation.



(a) Oscillation at 2 kHz



(b) Frequency response

Figure 10: Relationship between displacement and frequency.

5. Conclusion

Au and Au/GO micro-oscillator were fabricated by transfer-printing and inkjet printing. These micro-oscillators were deflected by electrostatic force. The Au micro-oscillator can be operated within 10 kHz. The lamination of GO nanoparticles enable Young's modulus of Au thin film to be improved.

Acknowledgments

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