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Characterization of quantum-weight generating cantilever device

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Abstract

Quantum-weight generating cantilever devices comprising a 20 micron-sized ring-shaped Niobium film deposited on the paddle of an ultrasoft single-crystalline silicon cantilever were characterized. High-quality niobium film was patterned by optical lithography and deposited using an ultra-high-vacuum sputter system within the micro-fabrication process of cantilevers, which adopts double-side reactive-ion-etching. The fabricated niobium film was observed using scanning electron microscope and atomic force microscope, and its superconducting property was also examined from low-temperature resistivity measurement. Thermal noise spectrum and frequency scan of cantilever vibration were measured at a room temperature to obtain resonance frequencies and quality factors of the device.

Key words: Quantum-weight, ultrasoft cantilever, niobium film

1. Introduction

Small force metrology, which is generally accepted as metrology for force below micro-Newton level, is attracting strong interest in pace with developing nano-science, but on the other hand staying almost uncultivated in a sense that there is too wide range from micro-Newton to zepto-Newton inside a simplified terminology of ‘small.’ The status of small force metrology at present is this; no direct SI-traceable force realization has been established even below 1 N.[1] To establish small force standard, whether applicable to the whole range or some specific ranges, new methods and approaches are being extensively searched and pursued by researchers including National Metrology Institutes, and increasing research activities will be devoted to realizing and comparing suggested methods.

Prevailing dead-weight method, which creates gravitaional force using standard weights, becomes no longer valid below micro-Newton level with growing uncertainties. Recently, a Microforce Realization and Measurement Project[1] was launched by National Institute of Science and Technology (NIST), with the goal of realizing force below 10 micro-Newton with a relative uncertainty of parts in 10^4. Therein, electrostatic standard force is created between two coaxial electrodes in maintaining a constant voltage. Related electrical units are traced to their standards based on Josephson and quantized Hall effects. Below nano-Newton or pico-Newton level, however, no force realization for standard has been suggested despite needs in precise measurement, for instance, testifying Casimir force[2], non-Newtonian gravitation, etc. On the other hand, unlike electrical units such as voltage, no attempt has been tried to directly use quantum phenomena in realizing a mechanical force, to our knowledge.

Very recently, a concept of quantum-based force realization utilizing magnetic fux quantization in a superconducting loop was presented by Korea Research Institute of Standards and Science (KRISS), where magnetic force exerted on flux quantums can be increased or decreased by a force step.[3] This force step is estimated as sub-pico-Newton level and may play a role of a weight with a quantum origin.

In this paper, we report on-going fabrication and characterization studies of quantum-weight generating cantilever device, as a key experimental step to realizing quantum-based force. A niobium thin film of ring shape is mounted on ultrasoft cantilevers with spring constant of $\sim 10^{-4}$ N/m in micro-fabrication process. To compare with the theoretical requirements from the conceptual design, we also observe the topography and the superconducting properties of niobium ring part and the mechanical properties of cantilever part.

2. Basic Principle of Force Realization With a Quantum Weight

A schematic of force realization with a quantum weight [3] is shown in Fig. 1.

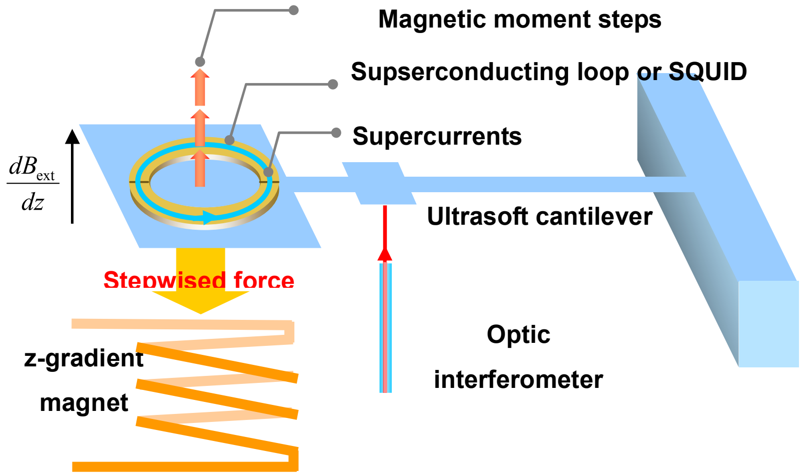

Figure 1. Schematic of quantum-weight generating cantilever device (Ref. [3]).

A superconducting loop is mounted on an ultrasoft micro-cantilever with an external magnetic field gradient applied in a perpendicular direction. In superconducting state, magnetic fluxoid through the loop is quantized, and the resultant magnetic moment has a component with constant steps. The step size is determined by fundamental constants such as electron charge and the length quantities of the loop.

In a calibrated magnetic field gradient, dB/dz, a force created on the superconducting loop is given by

$$F = n\, m_{\mathrm{Q}} \frac{dB_{\mathrm{ext}}}{\mathrm{dz}} \qquad (1)$$

where m_Q is a magnetic moment step by adding one flux quantum and n is an integer. If we consider an Nb ring of inner and outer radii, 5 μm and 10 μm respectively, and thickness of 50 nm, a force step is numerically estimated as 1.84×10^{-13} N in dB_{ext}/dz of 10 T/m.[3] This force may cause ~ 2 nm static displacement of a cantilever with k = 10^{-4} N/m, which is detectable with optic interferometer or lever. The field gradient, dB/dz, can be determined in-situ from the resonance frequency shift of the cantilever.

2.1. Micro-Fabrication of Superconducting Ring-Mounted Cantilever

For best feasibility, it is necessary before fabrication to determine the design parameters of superconducting ring-mounted cantilevers, such as the dimension and material of the cantilever and the superconducting ring parts. To detect such a small force as pico-Newton level, since a very small spring constant as $10^{-4} \sim 10^{-5}$ N/m is required, we designed a cantilever as a long bar shape, which is 4 um wide, 0.34 μm thick and up to 400 μm long, with a paddle for a ring and chose a single crystalline silicon as material for high quality factor, Q. For the ring part, the Nb material was chosen because of its readily accessible working temperatures below ~ 9 K [4], and inner and outer radii, a = 5 μm and b = 10 μm, were chosen so that they may increase a force step and reduce a background magnetic field effect at a same time[5].

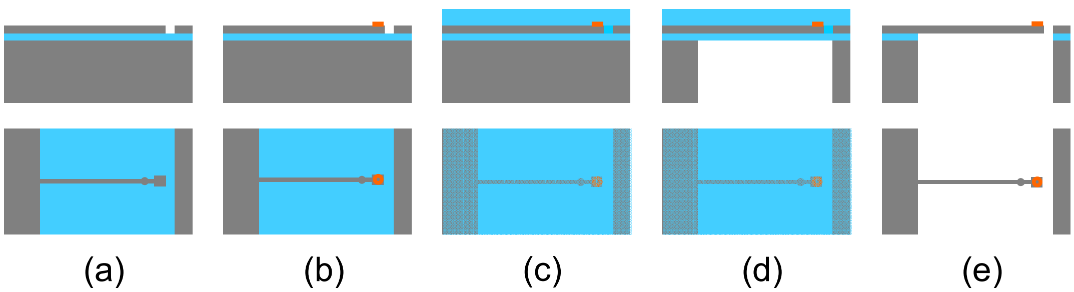

Figure 2. Fabrication process of quantum-weight generating cantilever devices.

The fabrication process of the superconducting ring-mounted cantilever is shown in Fig. 2, which will be dealt with in detail elsewhere[6]. The starting wafer was a silicon-on-Insulator (SOI) wafer with top side silicon of thickness 340 nm. The top side was patterned for cantilever shape using photolithography and the exposed silicon was then etched away in reactive ion etch (RIE). It was then patterned for ring shape and on exposed areas a high quality Nb film was deposited as thick as 50 nm nominally using a DC sputter, followed by passivation with 1 μm-thick silicon oxide layer.

Then, the bottom side was patterned to obtain windows and the exposed base silicon of thickness 450 μm was etched in a deep RIE. Finally, the silicon oxide was selectively removed using buffered oxide etchant, leaving cantilever chips connected weakly to a silicon frame; the cantilevers were then released in a critical point dryer.

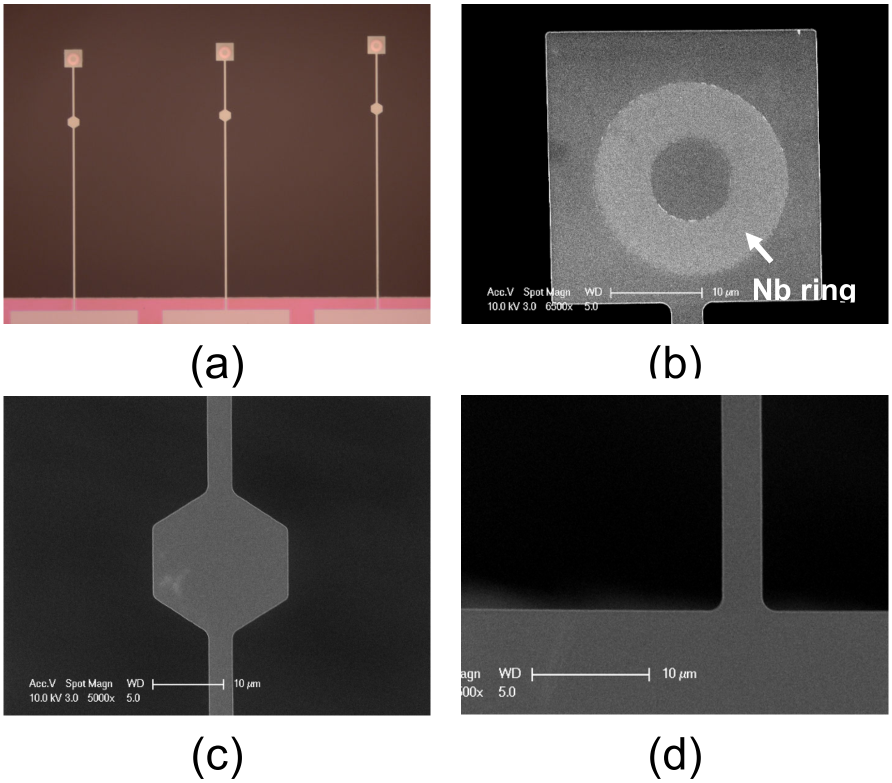

Figure 3. Optical microscope and scanning electron microscope images of quantum-weight generating cantilevers and their parts.

Figure 3 shows the released cantilevers in an optical microscope image (Fig. 3(a)) and the parts of them taken by a scanning electron microscope (SEM) with original magnification 5000x ~ 6500x (Fig. 3 (b)-(d)). As seen in Fig. 3 (a), one chip has multiple cantilevers of same width and thickness but slightly different lengths up to around 400 μm. The cantilevers have a paddle, on which a superconducting ring is mounted on, at the end and a hexagonal target for laser reflection in the middle. From the optical microscope and SEM images the silicon cantilever is found undistorted and to have a well-defined geometry and clean surface. Figure 3(b) shows a Nb ring of thickness ~ 50 nm on a silicon paddle. Dimensions, topography, and superconducting properties of a micro-patterned Nb thin film are analyzed in detail in the next section.

3. Characterization of a Micro-Fabricated Superconducting Film

Since accurate and direct determination of dimension and superconducting properties of the Nb film on a free standing cantilever is not easy, Nb film samples were prepared separately for characterization; Nb film strips were fabricated on a regular silicon wafer using almost same conditions as used for them on cantilevers. We varied the width and thickness of the Nb film to optimize its topographic and superconducting characteristics, but here we confine attention to the case corresponding to the design parameters determined theoretically[5].

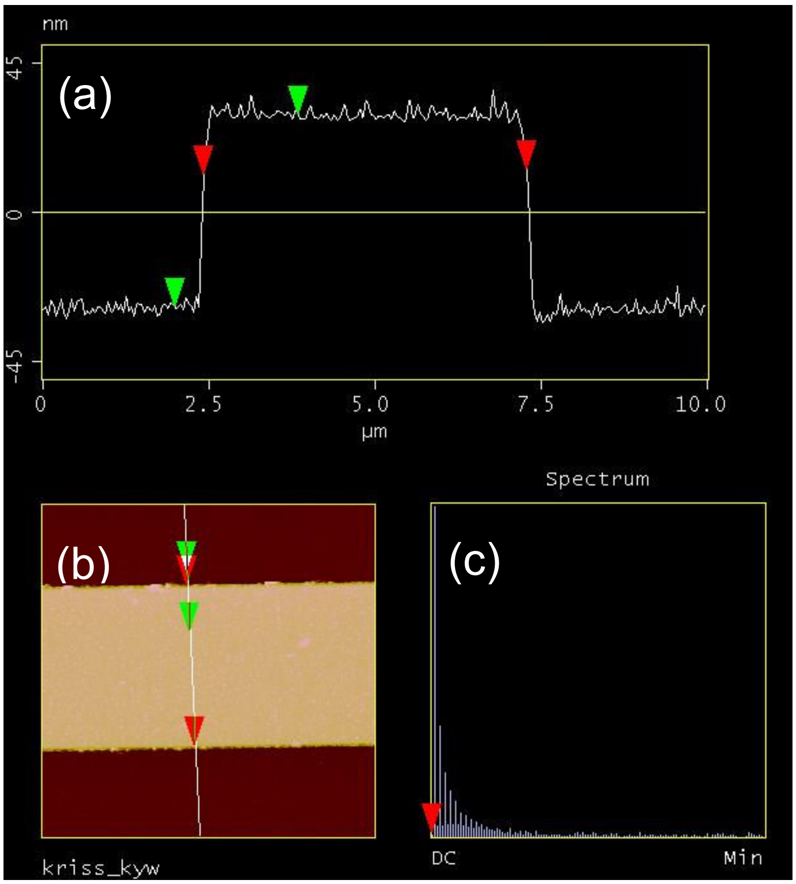

Figure 4. Topographic analysis of a deposited Nb film strip of nominal width 5 um and thickness 50 nm using an atomic force microscopy.

Figure 4 shows the result of topographic analysis for a deposited Nb film strip of nominal width 5 μm and thickness 50 nm using an atomic force microscopy (Veeco LD3100). After a topographic image of size 10 μm x 10 μm was obtained in a tapping mode, a height vs. position plot was constructed as in Fig. 4 (a) from data along a white path in Fig. 4 (b) which is perpendicular to the Nb strip. From the height (position) difference between two green (red) triangles, the thickness (width) of the Nb strip is deduced as 58.4 nm (4.84 μm) similar to nominal values.

To make sure the quality of the superconducting (Nb) thin film, the temperature dependence of electrical resistivity was measured at low temperatures from 5 K to 14 K in zero external magnetic field. As seen in Fig. 5, the superconducting property of the deposited Nb thin film is found quite good; the superconducting transition is very sharp and its temperature is 7 K, which is a little lower than the value of bulk Nb due to thickness but well higher than our target temperature, ~ 4 K, of operation.

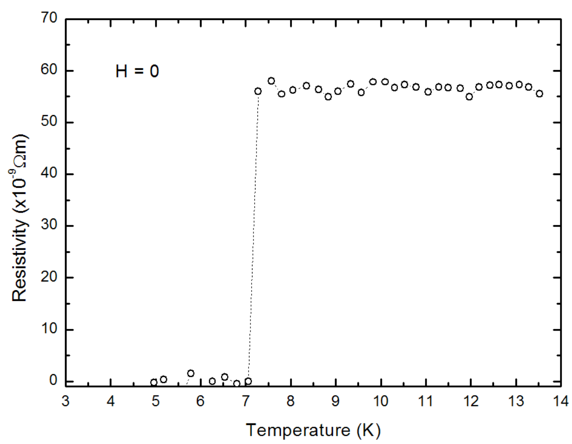

Figure 5. Superconducting property of a fabricated Nb thin film in zero magnetic field.

4. Mechanical Properties of an Ultra-Soft Cantilever Device

To observe the mechanical properties of cantilever devices, we measured their vibration using optic interferometer with laser of wavelength 1310 nm and in high vacuum of pressure ~ 10^{-5} Torr to minimize air damping. We observed the vibration in two modes; (a) frequency scan mode and (b) thermal noise spectrum mode. In the first mode, we scan the frequency of ac voltage applied to the piezo-actuator which vibrates a cantilever, and measure the output of the lock-in amplifier connected to the interferometer at the driving frequencies. In the second mode, we obtain the time series data of cantilever deflection due to thermal fluctuation and convert them into power spectrum density by Fourier transformation; in this case there is no applied voltage to the piezo-actuator.

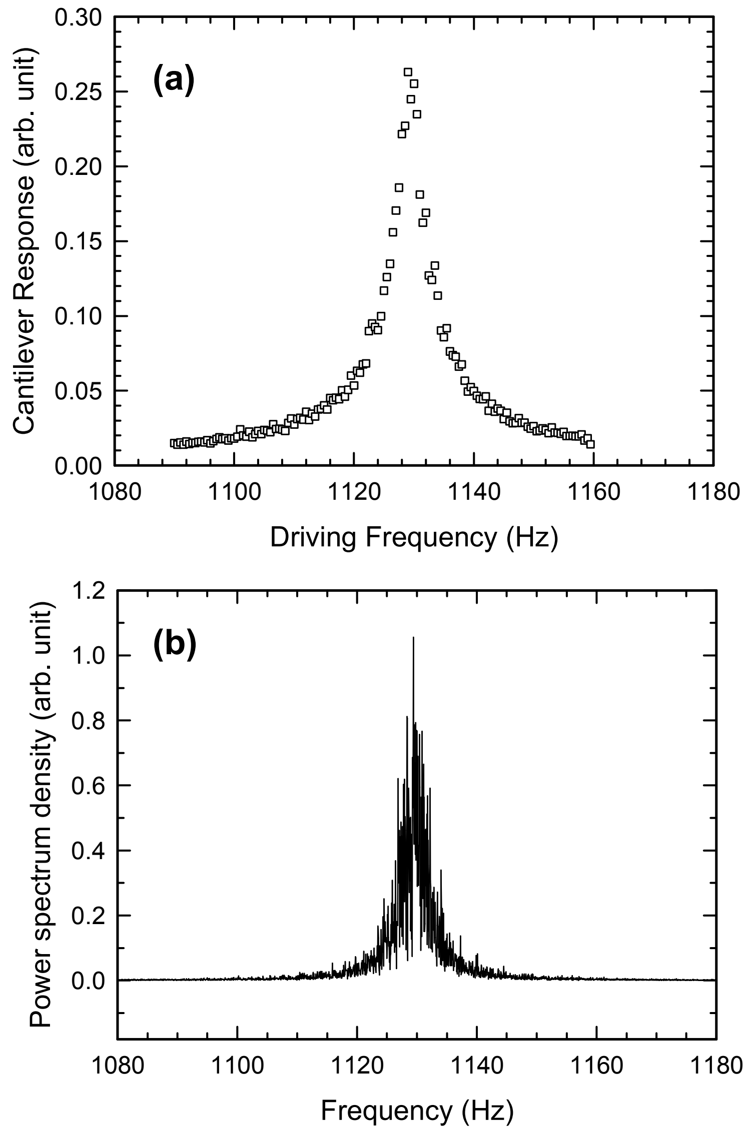

Figure 6. Cantilever vibration in (a) frequency scan mode and (b) thermal noise spectrum mode.

Figure 6 shows the results obtained in both modes at a room temperature. From the two results, the values of the first resonance frequency are deduced as 1129.3 Hz and 1129.6 Hz, respectively, which coincide well with each other. They are a little lower than the prediction of our finite element analysis, 1350.3 Hz, which may be attributed to smaller widths of fabricated cantilevers than nominal values taken in the analysis but needs further studies. The quality factor of the cantilever was determined to be about 220 from the frequency scan.

5. Conclusions

KRISS has micro-fabricated quantum-weight generating cantilever devices, which are a key to realizing a concept of quantum-based force generation as a possible standard force in pico-Newton level. In characterizing the devices, the topography and the electrical properties were studied for deposited superconducting thin film part of niobium, and the mechanical properties as well as the geometry were for cantilever part, through various measurement tools such as SEM, AFM, lab-made low-temperature resistance measurement system, and high-vacuum optic interferometer system. Their properties are to be developed continuously, but are even acceptable so that the fabricated devices can be used in feasibility-test experiments.

References

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