FABRICATION OF NANOMECHANICAL RESONATOR WITH NON-LOCAL SPIN VALVE STRUCTURE FOR SPIN DETECTION AND CONTROL

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ABSTRACT

We have fabricated ultra-sensitive nanomechanical resonators with an integrated non-local spin valve structure. The obtained sensitivity is 1.42×10^{-17} N for the flexural mode and 1.68×10^{-18} N for the torsional mode, which indicates that the resonator is able to detect spin relaxation in terms of torque measurements.

INTRODUCTION

There has been considerable interest in studying spin transport properties of ferromagnetic (FM) and non-magnetic (NM) hybrid structures because of their potential applications as spin-electronic devices [1-4]. Especially, electrical spin injection from FM into NM is important technique for developing low-power dissipation spintronic devices. Spins have angular momentum, and a change in the angular momentum due to spin diffusion should create a mechanical torque (Fig. 1). Mechanical detection of such spin-induced torques is an important step for the realization of spin-integrated MEMS devices.

The nanomechanical resonator is a promising technique to detect the mechanical torque produced by a few or single spin. Based on the use of nanofabrication techniques developed in the semiconductor industry, numerous studies using nanodevices have been reported [5]. A mechanical detection is of great interest for a number of applications, including sensors for mass, electrical, magnetometry of magnetic nano-particles, and various types of force microscopy because of ultra-sensitivity [6-9]. Recently, nanomechanical devices have provided a clearest picture to date of persistent currents in normal metallic rings and the result of single spin detection [10, 11].

In general, nanomechanical devices which have high resonant frequencies and low spring constants can provide high sensitivity in the detection of the signal. The force sensitivity in the vibration techniques is known to depend critically upon the resonant frequency, amplitude, and quality factor Q, and stiffness of the used mechanical device [11, 12]. The sensitivity of the nanomechanical device can be designed using the following equation of the minimum detectable force:

$$\delta F_{min} = \sqrt{\frac{4kk_BT}{2\pi f_0 Q}} \tag{1}$$

where k is the spring constant, k_B is the Boltzmann constant, T is the temperature, f_0 the resonant frequency and Q the quality factor [13,14]. From the Eq. (1), using higher resonant mode of nanomechanical devices promises higher senisitivity in the mechanical detection. Compared with flexure modes, the torsional mode can provide an improved sensitivity owing to the higher resonant frequency and lower spring constant [15].

In this work, we have fabricated an ultra-sensitive nanomechanical torsional resonator with integrated non-local spin valve structure in order to detect small torque signals induced by spin relaxation around the FM|NM interface.

EXPERIMENTAL

The resonator device has a torsional paddle supported by a pair of thin and long parallel tethers. For torsional motion, the torsional paddle rotates around the axis defined by two tethers. The resonant frequency and the spring constant of a torsional mode can be expressed as

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{2J_TG}{L_TI}}, \tag{2}$$

$$k = \frac{J_TG}{L_T} \tag{3}$$

where G is shear modulus of elasticity, L_T is the tether length and J_T is the torsional area moment of inertia, which for rectangular cross section is

$$J_T = w_Tt^3 \times \left(\frac{1}{3} - 0.21 \times \frac{t}{w_T} \times \left(1 - \frac{w_T^4}{12 \times t^4}\right)\right) \tag{4}$$

where w_T is the tether width, t is the thickness. I is the total

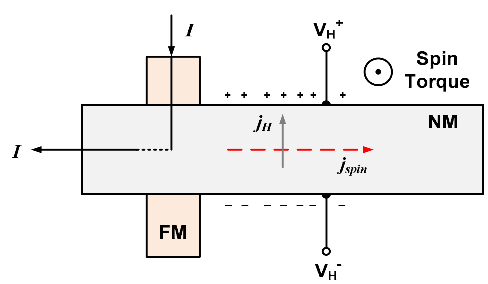

Figure 1: Schematic illustration of a non-local spin valve structure and the mechanical torque generated by spin transport.

mass moment of inertia from both the tethers and the paddle which is given by:

$$I = I_{tether} + I_{paddle} = \frac{1}{6}\rho t L_T w_T (w_T^2 + t^2) + \frac{1}{12}\rho t w L^3 \quad (5)$$

where ρ is the density, l is the paddle length and w is the paddle width. As mentioned above, high force sensitivity is obtained by a high resonant frequency and a low spring constant. According to Eqs. (2)-(5), this is realized by a torsional resonator consists of a small paddle and a thin, narrow, and, most importantly, long tether. Thus we designed the resonator tether with a total length of 150 μm and width of 1.5 μm and torsional paddle with 3 μm × 8 μm, which results the resonance frequencies in the MHz range.

Figure 2 shows the fabrication process of the Si resonator with metal nanowires of spin valve structure, which begins from a silicon on insulator (SOI) wafer with a 340 nm in thickness device layer and 2 μm in thickness silicon oxide layer (Fig 2(a)). First, the electrode pads were fabricated using an electron beam (EB) lithography system (ELS-7500; ELIONIX Inc.) and a lift-off process. The bilayer resist consisting of 300-nm-thick methyl methacrylate (MMA) / 150-nm-thick polymethyl methacrylate (PMMA) was prepared on a SOI substrate. After the EB lithography with 50 kV acceleration voltage and the development, the mask patterns were made on the resist layer. Au/Ti layer for electrode pad was deposited using EB evaporation and lift-off, as shown in Fig 2(b). Second, the spin-valve structure was prepared by means of the undercut resist mask and shadow evaporation technique. The pattern of spin valve structure was performed by EB lithography on the PMMA/MMA resist layer. Then, the permalloy (Py) layer was formed by EB evaporation at an angle of 45 degree from the electron beam direction. After the Py deposition, the Cu was evaporated at an angle of 0 degree in the same chamber, as shown in Fig 2(c). The resonator structure was patterned by a dual beam focused ion beam (FIB) / scanning electron microscopy (SEM) milling system (Versa3D Dual Beam; FEI Company) with 30 kV and 0.5 nA Ga+ ions. The dual beam FIB/SEM system can fabricate the resonator pattern without damage of the spin valve structure in the correct position, as shown in Fig 2(d). Then, the silicon oxide layer was etched and the resonator structure was released from the substrate by HF vapor-phase etching, as shown in Fig 2(e). This technique is an effective etching method to release fragile and suspended structures without stiction due to the surface tension during drying process. Finally, electrical contacts between the fabricated NEMS device and the PCB were made by wire bonding (Fig 2(f)).

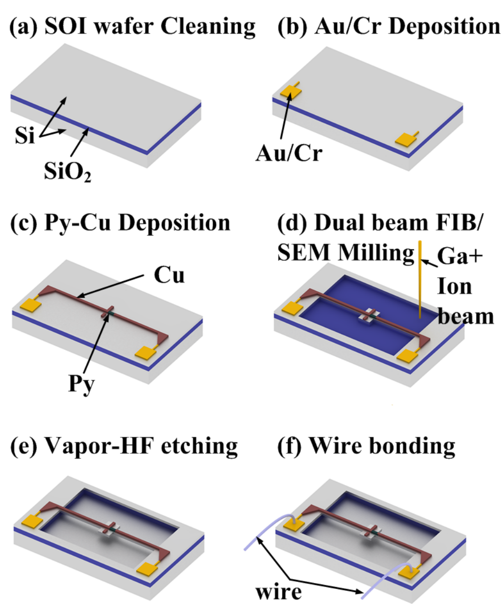

Figure 2: Schematic illustration of the fabrication process of Si resonator.

RESULTS AND DISCUSSIONS

Figure 3 shows a fabricated Si torsional resonator with metal nanowires for spin torque detection and control. The resonator consists of the 150 μm × 1.2 μm tether, and the 2.5 μm × 7.5 μm torsional paddle. The metal nanowires are 200 nm in width, with a 30-nm-thick Py layer deposited on the FM side and a 100-nm-thick Cu layer on the NM side.

Mechanical simulations of the torsional resonator is conducted using COMSOL Multiphysics software [16] in order to assign resonant vibration modes. The simulation results show that the nanomechanical resonator have nine resonance frequencies in the frequency range from 0 Hz to 3.5 MHz: six frequencies of flexural mode, two frequencies of lateral mode, and one frequency of torsional mode.

The thermal-vibration resonant spectrum of the fabricated torsional resonator was measured with a laser Doppler vibrometer (MSA-100-3D; Polytec Inc.) at room temperature in vacuum of ~10^{-4} Pa. The resonator has the four peaks at 376.93 kHz, 1.20 MHz, 2.38 MHz, and 2.75 MHz, as shown in figure 4(b). By comparing with a numerical

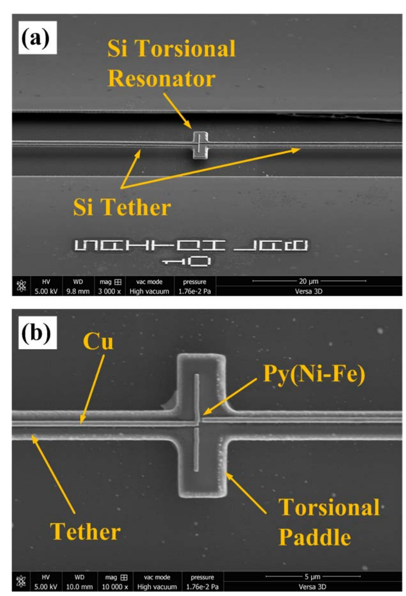

Figure 3: SEM image of Si resonator with integrated non-local spin valve structure.

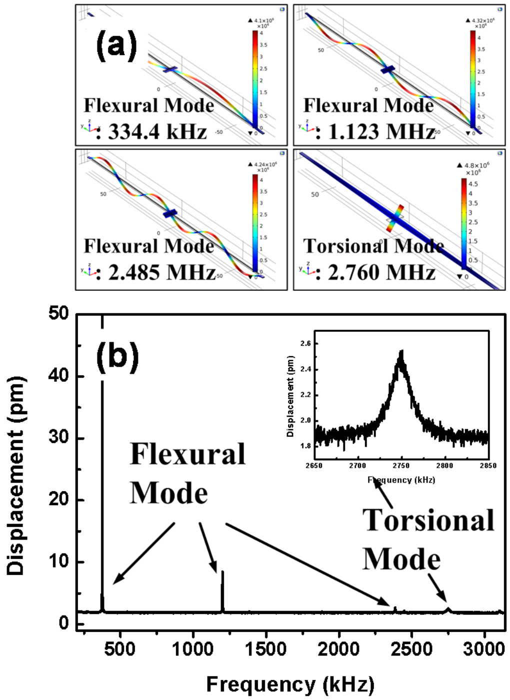

Figure 4: (a) Simulation results using COMSOL Multiphysics. (b) The thermal vibration resonant spectrum of the fabricated resonator.

simulation results using COMSOL Multiphysics software in Fig. 4(a), we assigned these peaks as resonance modes of the nanomechanical resonator. The lower resonance frequencies (376.93 kHz, 1.20 MHz and 2.38 MHz) correspond to the flexural modes, while the highest one (2.75 MHz) the torsional vibrational mode. The quality factors are 1400 for the flexural mode and 100 for the torsional mode, respectively. The thermally limited minimum detectable forces of the fabricated torsional resonator are estimated to be 1.42×10^{-17} N (flexural mode) and 1.68×10^{-18} N (torsional mode) using Eq. (1).

The magnitude of the force generated due to diffusion of the spin angular momentum S can be estimated using the following equation [17]:

$$S = \frac{\hbar}{2}\frac{I_S}{e}, \tag{6}$$

where $\hbar$ is the Planck constant, I_s is the spin current and e is the electric charge, respectively. Then, I_S is assumed to be constant and exists only in the range of spin diffusion length λ. Spin relaxation results in a change in the angular momentum, which then affects the resonator vibration as a mechanical torque. A generated force by the spin-induced torque on the resonator, F can be written as

$$F = \frac{\hbar I_S}{2e\lambda_N}. \tag{7}$$

Here, λ_N is the diffusion length into the material. In case of the copper with $\lambda_{Cu} \sim 600$ nm [18], the generated force is estimated to be 1.3×10^{-11} N/A. From the sensitivity of our resonator, we expect that the fabricated resonator is able to detect the generated spin torque by the elctric current with greater than 1 μA.

A schematic of the experimental setup of spin-diffusion detection is shown in figure 5. We apply an electric current to the resonator through a resistance box in series using a function generator in the frequency range from 0 to 15 MHz and the voltage range from 0 to 20 V. The spins are injected by applying an electric current across the FM to NM interface and accumulate around their interface. The accumulated spins are expected to diffuse in the NM layer on the torsional paddle and generate a mechanical vibration. Then, the vibration caused by spin torque is measured with a laser Doppler vibrometer (MSA-100-3D; Polytec Inc.) at room temperature. The measurement is performed in a high vacuum 10^{-4} Pa for high sensitivity. External magnetic fields were applied to the resonator using electromagnets along the parallel direction to the FM within the silicon plane. The resonant frequency is expected to change in response to additional spin torque because external force action results in the change of the resonator effective stiffness.

Figure 6(a) shows that the thermal vibration resonant spectrum for various values of the electric current from 0 mA to 1 mA. Resonant frequencies did not change with electric current amplitudes. After the measurements, fracture of metal wires on the torsional paddle structure was found in a SEM image as shown in figure 6(b). It means that spin diffusion and spin relaxation did not occur because electric current did not flow into the spin valve structure. Although the exact reason for breakage is unknown, it may be due to static electricity generated upon wiring and/or application of electric currents. The improvement of the measurement setup is required for the mechanical detection of spin relaxation at room temperature.

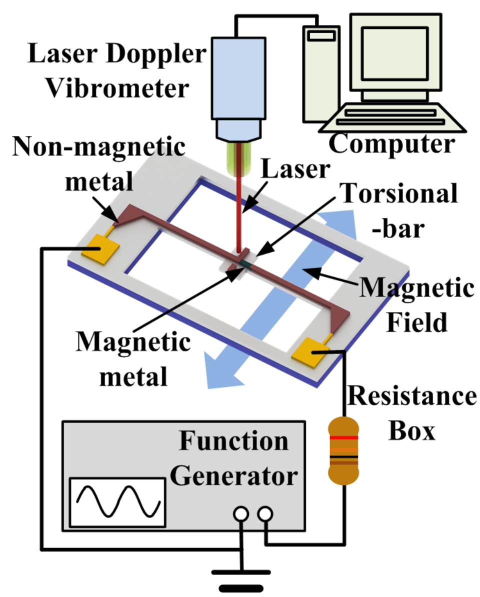

Figure 5: Schematic illustration of the experimental apparatus.

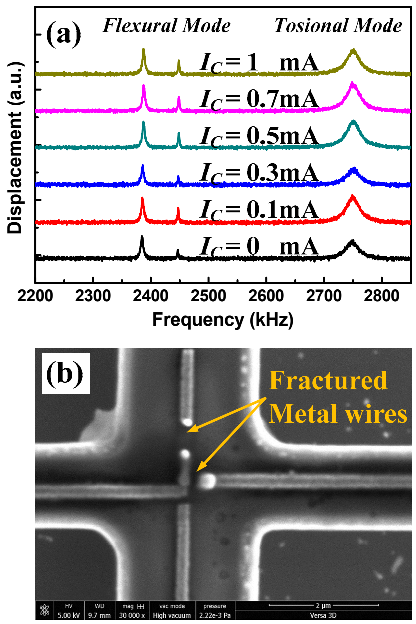

Figure 6: (a) The thermal vibration resonant spectrum for various value of the electric current. (b) SEM image of the fractured metal wires on Si resonator.

CONCLUSIONS

An attonewton-sensitive torsional resonator with a spin valve structure has been fabricated based on a top-down fabrication process. The minimum detectable forces of the fabricated resonator are 1.42×10^{-17} N (flexural mode) and 1.68×10^{-18} N (torsional mode), which are much smaller than expected magnitudes of spin relaxation forces generated in the spin valve structure. However, the vibrational modes did not change with applied electric current amplitudes. This is probably because spins do not diffused into the torsional paddle due to accidental breakage of the metal wire in measurements. To observe spin-diffusion torque, a static electricity discharge system will be required in all processes in order to prevent for the breakage. Nevertheless, we believe that the fabricated nanomechanical resonator will be a suitable tool for detection and control of spin signal in spintronics.

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