Fabrication and Characterization of All-Thin-Film Multiferroic Cantilevers for Magnetic Energy Harvesting

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Abstract:
The electromagnetic energy harvesting properties of all-thin-film magnetoelectric (ME) heterostructures are measured. The devices are built on a silicon oxide/nitride/oxide (ONO) stack, and the ME layers consist of a magnetostrictive Fe$_{0.7}$Ga$_{0.3}$ thin film and a Pb(Zr$_{0.52}$Ti$_{0.48}$)O$_3$ piezoelectric thin film. The $Q$-factor of the mechanical resonance of the cantilevers is ≈ 2000 in vacuum. The device resonant frequency displays a pronounced DC bias magnetic field dependence. The harvested peak power at 1 Oe is 0.7 mW/cm$^3$ (RMS) at the resonant frequency (3.8 kHz) with a load impedance of 12.5 kΩ.

Summary of Research:
In the emerging hybrid field of spintronics and straintronics, the multiferroic materials have attracted significant interest due to coexistence of ferromagnetism and ferroelectricity as well as their coupling. In laminated heterostructure systems, strong magnetoelectric (ME) coupling was observed due to strain-mediated interaction across the interface between magnetostrictive and piezoelectric phases. Such multiferroic heterostructures were used in bulk (centimeter-sized) devices for low magnetic noise measurements at room temperature and magnetic energy harvesting. Due to their low quality factor, $Q$, and low ME coefficient, $a_{ME}$, as well their large size with unsuitability for integration with microfabricated peripheral circuits, the multiferroic bulk devices need to be improved by miniaturizing them on microelectromechanical systems (MEMS) platforms or magnetomechanical microsystems.

We have developed multiferroic sensors that consist of free-standing Pb(Zr,Ti)O$_3$ (PZT) magnetostrictive cantilevers (Figure 1). The thin-film heterostructure is on a Si substrate with a plasma-enhanced chemical vapor deposited (PECVD) oxide/nitride/oxide (ONO) stack. A 20 nm/100 nm Ti/Pt layer is sputtered at 430°C to form the bottom electrode of the piezoelectric part of devices. A ~ 500 nm PZT (e.g., Pb(Zr$_{0.52}$Ti$_{0.48}$)O$_3$) layer is spun by a sol-gel process. The PZT layer is covered by another 35 nm Pt buffer layer by sputtering at 305°C. A 500 nm Fe$_{0.7}$Ga$_{0.3}$ layer is then sputtered at room temperature.

![Figure 1: A SEM micrograph of multiferroic harvesters. The devices are 950 nm long and 200 nm wide released cantilevers. The contact pads of the device are located at the base of the cantilever. Inset: Detailed SEM micrograph of the device heterostructure.](image1.png)

![Figure 2: Energy harvested RMS voltage at bias field $H_{AC} = 1$ Oe and corresponding resonant frequency of 3833.1 Hz. Also, one displays the raw power measured as a function of loading impedance at resonance. The harvested AC magnetic field is $H_{AC} = 1$ Oe RMS.](image2.png)
temperature. The Pt buffer layer between PZT and Fe$_{0.7}$Ga$_{0.3}$ films has the role to improve the adhesion of the films.

A very important issue in making the cantilever-based sensors is the film-stress engineering of the heterostructure. The design allows a strategically vertical shift of the silicon ONO stack in the cantilever by modifying the thickness of the first and last layers of the silicon oxide. This will also alternate the stress distributions in the stack ensuring a final planar structure of the beam. The first silicon oxide layer grown on the silicon substrate has a thickness of 400 nm. Then, a 75 nm low stress tensile-type silicon nitride and a 100 nm silicon oxide are grown and so on up to six similar layers of silicon nitride. This structure with individual thinner silicon nitride layers instead of one single thick layer helps avoiding film cracks during the subsequent rapid thermal annealing (RTA) processes. The last oxide layer is deposited to complete a 3.8 μm thick ONO stack (Figure 1).

Figure 2 shows the experimental results for energy harvesting from a single multiferroic device. The AC magnetic field was maintained at 1 Oe RMS. The power output has a peak that occurs for a load impedance of 12.5 kΩ. To determine the power density of the multiferroic harvester, an effective volume (950 μm × 200 μm × 0.5 μm) must be taken into account that involves the freestanding length of the cantilever and the thickness of the poled (PZT) piezo-film. In this respect, the measured peak power density is 0.71 mW/cm$^3$. This value is close to other reported harvested power densities at 1 Oe RMS for bulk devices.

We have found that the resonant frequency of the present ME devices exhibits strong dependency on the magnitude and the sweeping direction of the DC bias field (H) (Figure 3). This fact indicates that the resonant frequency of the first-order flexural mode of the devices is determined not only by the mechanical properties of the devices, but also by the magnetic properties. The discontinuity in the DC field dependence of the resonant frequency occurs at 77 Oe (Figure 4). This value agrees with the coercive field of the 500 nm thick Fe$_{0.7}$Ga$_{0.3}$ films measured by VSM (vibrating sample magnetometry). A similar behavior was previously observed both in NEMS (nano-electromechanical systems) based devices and in larger clamped beams.

An interesting consequence of the field dependent $f_R$ is that as seen in Figure 3 the device can be operated at zero DC magnetic bias field with a relatively high ME coefficient as long as the AC field frequency is at the $f_R$ (H = 0). Removing the necessity to apply DC bias significantly simplifies the operation setup of these devices for both magnetic field sensing and energy harvesting schemes.

References: