FABRICATION OF DOUBLE CANTILEVER SENSOR FOR STUDY OF MAGNETIC MICROSTRUCTURES

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1. Introduction

Magnetism is an interesting and fast developing field that brings many applications focused on everyday life. The applications include information coding by a magnetic state, which is nowadays the basis of the most massive information storage [1]. Magnetic particle-like configurations (domain walls, vortices, skyrmions, e.g.) provide a route to novel approaches to ultra-dense information storage and solid-state spin-based information processing devices, for example, the concept of racetrack memory, in which a train of up and down magnetic domains is moved electrically along a magnetic track. Their stability makes it promising for future applications in non-volatile memory and spintronics devices [1]. Furthermore, the magnetic alternative to semiconductor microelectronics–based computing promises highly efficient and ultra-low-power operation close to the theoretical limit of thermodynamic efficiency [2].

The knowledge of the magnetic properties of structures is of fundamental interest and all these novel micro- and nano-magnetic concepts have to be examined during research using a high-resolution method that does not perturb the magnetic state of the system. This is also necessary for the development of future technical applications.

One of the highly sensitive force and torque sensors suitable for detecting magnetic properties of very small samples are micromechanical cantilevers. The torque acting on the magnetic structure placed at the free end of a cantilever results in a change of the resonant frequency of an oscillating cantilever depending on the applied magnetic field. The magnetic properties are derived from the frequency response versus magnetic field curve (f –H curve). The dimensions of the cantilever and the frequency noise determine the detection sensitivity [3]. Great advantage of such sensors is that they transduce magnetic forces into measurement of frequency, which can be measured with very high accuracy.

Examined structures can be placed on cantilever by several methods. Most common are fabrication from planar substrate using lithography [4,5] and also by placing and gluing of magnetic particles on cantilever by micromanipulator and local deposition [6]. These are complex processes and have several drawbacks. Huge obstacles, that are not easily resolved, are coating of resist film on 3D prestructured substrates and erosion of thin magnetic layers during final release of cantilevers in wet etch. On the other hand, gluing of particles on cantilever involves a risk of negatively influencing cantilever´s mechanical properties. There are several alternative methods how to overcome these obstacles. In our previous work we presented an additive method involving modified resist spin-coating, e-beam lithography, deposition and lift-off [7]. In this contribution we present the opposite - substractive method involving focused ion beam (FIB) milling of deposited magnetic thin films. By this means it is possible to resolve previously mentioned obstacles, because it is not necessary to apply resist on cantilevers and as well as structures are prepared directly on a cantilever without the need of gluing them.

2. Fabrication

The fabrication process started with commercial silicon tipless AFM probes (μmasch HQ:NSC35tipless). In the beginning, the 40 nm thin film of magnetic material Permalloy $Ni_{80}Fe_{20}$ (Py) was deposited on cantilevers by electron beam evaporation. In the next steps, FIB workstation using a Ga^+ liquid metal ion source accelerated at 30 kV was used to cut cantilevers and prepare structures by FIB milling. Triangular-shaped ends of cantilevers were cut off straight using 5nA Ga^+ ion beam current. Cutting was done from the backside to prevent from contamination of Ga to the magnetic material. Cantilevers were cut into halves, firstly by 3nA current resulting in wide space between cantilever halves. Subsequently, near the end where magnetic structures would be patterned, they were cut by 100pA resulting in narrow space between cantilever halves. They were cut not exactly in the middle, so they are not definite halves. Etching of redundant Py on the area of whole cantilever was done using 3nA current. Magnetic structures were patterned using 100 pA current. Patterning software allowed to generate the milled pattern from a bitmap image. Py thin film was patterned into two ellipses, longer and shorter one. Their sizes were designed to be 14 μm × 2.5 μm and 7 μm × 4 μm, respectively. Gap between the edges of ellipses was designed to be approximately 0.5 μm. One of the fabricated cantilever sensors with the best results is shown in **Fig.1** and **Fig.2**.

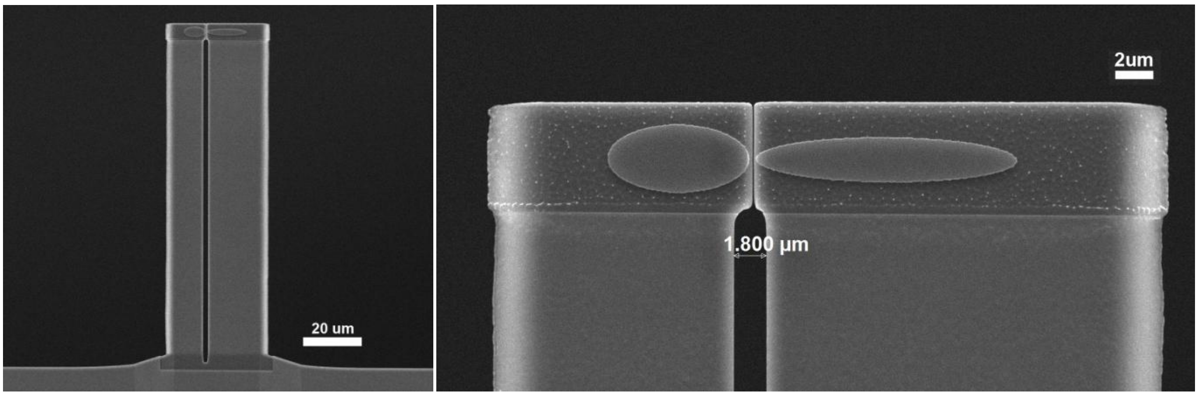

Fig.1: *SEM images of fabricated cantilever sensor.*
a) Whole cantilever. It was 99 μm long and 39 μm wide.
b) Detail of the end of cantilever. Cantilever halves were 1.8 μm apart (wide space).

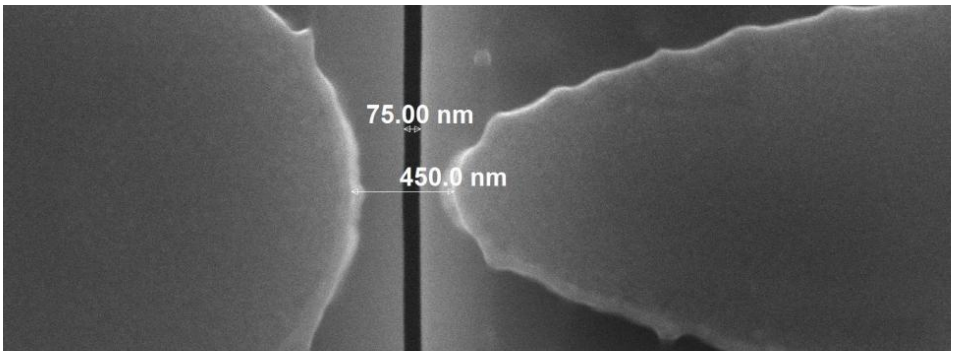

Fig.2: *SEM image of narrow space between cantilever halves. They were 75 nm apart and magnetic ellipses were separated by 450 nm place.*

3. Design and characterization of sensor

We proposed a different design of cantilever sensor for study of magnetic microstructures. It consists of cantilever, which is cut into two separated halves and a micrometric-sized magnetic ellipse is prepared on each of them. One of the ellipses is chosen to be in single domain state, so according to theory of micromagnetism it has larger aspect ratio, it is narrow and long. Second one is chosen to be in vortex state, so it has smaller aspect ratio and it is wide and short. Prepared ellipses on cantilever are shown in **Fig.3**. Corresponding remanent magnetic state of sample with the same ellipses measured by magnetic force microscopy (MFM) is shown in **Fig.4**. This sample was prepared on planar substrate with the same technologic parameters.

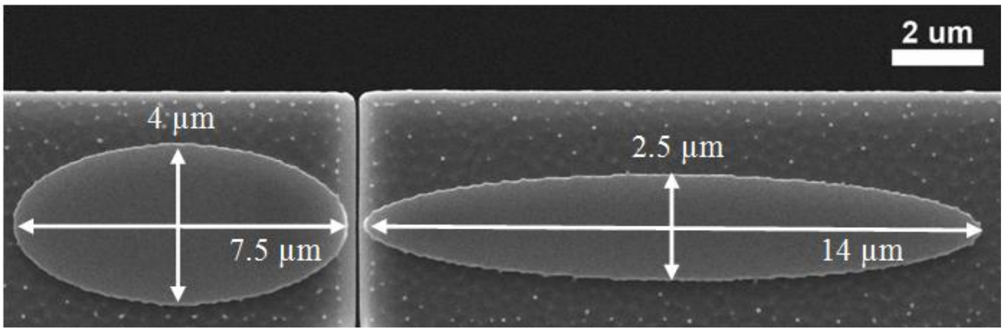

Fig.3: *SEM image of ellipses.*

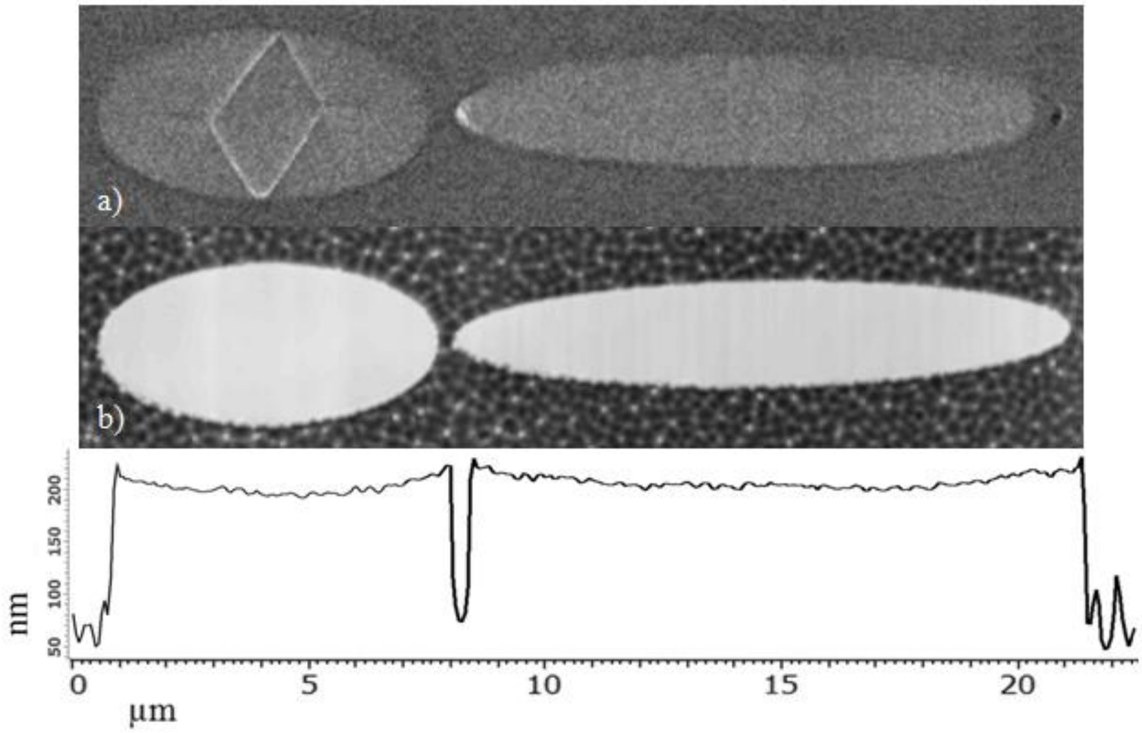

Fig.4: *a) MFM image of ellipses. They were magnetized in 100 mT external field and MFM was measured without field. The smaller ellipse is in vortex state. A diamond shape that is visible in the middle corresponds to two vortices. The longer ellipse is in single domain state, lighter and darker areas visible near the ends correspond to south and north pole of magnetic dipole. b) AFM topography corresponding to MFM. Underneath is one line from topography, cross-section of ellipses in the middle.*

Since magnetic ellipses are close to each other, their magnetic moments interact. The smaller ellipse can be introduced into single domain state by applying external magnetic field, which is strong enough to arrange all magnetic moments into the same direction. In this case there are attractive forces acting between the ellipses that create magnetic coupling between cantilevers. They will have the same value of resonance frequency and there will be visible one resonance peak when measuring the resonance spectrum. When reducing the applied external field, at certain value vortices are introduced into smaller ellipse and attractive forces between ellipses (i.e. coupling between cantilevers) disappear. Each cantilever will have different resonance frequency and there will be visible two resonance peaks in the spectrum. This feature is promising to be used for study of magnetic properties of prepared magnetic structures, that will be fast, sensitive and non invasive. Sensitivity of cantilever can be enhanced by decreasing the thickness of cantilevers. That can be done by FIB etching from backside of the cantilevers and do not affect the magnetic structures.

4. Conclusion and future work

The authors presented a fabrication of a cantilever-based sensor with magnetic microstructures. It was done by subtractive method where deposited magnetic permalloy thin films were patterned and cut by FIB milling. Cantilevers were cut into halves and two ellipses with different aspect ratio were patterned at their free end. We proposed a novel design of cantilever sensor. One of the ellipses was in single domain magnetic state and the other one was in vortex state. By applying external magnetic field both ellipses can be introduced into single domain state and by means of attractive magnetic forces coupling between cantilevers can be created. Coupled cantilevers will have the same resonance frequency; hence this case can be distinguished by measuring the resonance spectrum as single resonance peak. Reducing the external magnetic field, vortices can be introduced into the smaller ellipse and the coupling disappears. This case can be observed by double resonance peak. By this means we expect we would be able to study magnetic properties of prepared magnetic structures. We are heading towards experimental technique for non-invasive measuring magnetism of small magnetic particles and we consider presented double cantilever sensor as interesting and promising method.

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