CANTILEVER SENSOR FOR STUDY OF MAGNETIC MICROSTRUCTURES

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1. Introduction

Micro-electro-mechanical systems (MEMS) have been attracting attention for research in recent years, and nowadays play important roles as key devices in various systems. MEMS devices often employ free standing structures, such as beams and plates, over a cavity serving as space for structures to bend or oscillate. Much of commercial MEMS technology is silicon based since silicon microfabrication is now well established, with three-dimensional structures being fabricated from a silicon platform using lithographic processes. Cantilever-based sensors are one of the applications of MEMS. [1], [2]

Some of the first approaches to develop cantilever-based sensors were based on the fabrication from planar silicon-on-insulator (SOI) substrates. Cantilevers were defined in a device layer by photolithography and then chemically etched. Generally, any material could be added on the top of the device layer and further patterned by electron beam lithography (EBL). However, a common obstacle is that acid, which is used to remove the buried oxide layer (BOx) in a SOI wafer to release mechanical structures, also etches a variety of other materials. These include widely used metallic and magnetic thin films (Al, Ti, Co, and Ni). Such films patterned onto device layers before BOx etching will be heavily eroded during the release step. [3], [4], [5]

Subsequent approaches were based on the fabrication of devices (cantilevers, resonators) and then defining the nanostructures additionally. However, spin coating is not suitable for 3D substrates since it is difficult to obtain a uniform resist film. Therefore alternative methods of resist deposition are used, such as resist deposition from water surface [6], low-viscosity diluted resist [7], spray coating [8], [9], dip coating [10], and resist evaporating [11]. These are all complex processes and require special equipment.

In this paper the authors propose a simple method for fabrication of a prototype cantilever-based sensor with magnetic microstructures. For this purpose, to demonstrate the functionality, the magnetic structures were defined on a standard silicon atomic force microscopy (AFM) cantilever. The authors introduced an alternative solution to deal with the inhomogenity of spin-coated resist film. For the actual process of spin-coating two identical AFM chips were glued together to achieve a planar surface. Chips were finally separated during lift-off process, which released the bare cantilever. Afterwards, the final shape of cantilever sensor was cut by focus ion beam (FIB) milling. This fabrication process can be generalized for patterning various shapes of microstructures and thus fabrication of distinct prototype cantilever sensors.

2. Fabrication

The fabrication process started with two standard commercial silicon AFM chips. They were at first cleaned in oxygen plasma for 3 minutes. One of them was then glued on a flat substrate, where a drop of polymethyl-methacrylate (PMMA) was used as a gluing agent.

The PMMA was then dried on a hot plate at 170 °C for 1 min. The other chip had its cantilever removed. This "cantilever-less" chip was then inserted below the cantilever of the glued chip. This step is schematically depicted in Fig.1a). Aforementioned procedure was performed using a micromanipulator. The chip was finally fixed with a spring to the substrate. The substrate, together with chips in this configuration, was loaded on the spin coater. Several drops of undiluted PMMA 950K resist were spin coated for 45 s at 5000 rpm onto the chips´ surface. The resist was then baked on a hot plate at 170 °C for 2 min. Chips coated with resist film can be seen in Fig.2b). EBL was performed using Raith EBL system with acceleration voltage of 30 kV and exposure dose 300 $\mu C/cm^2$.

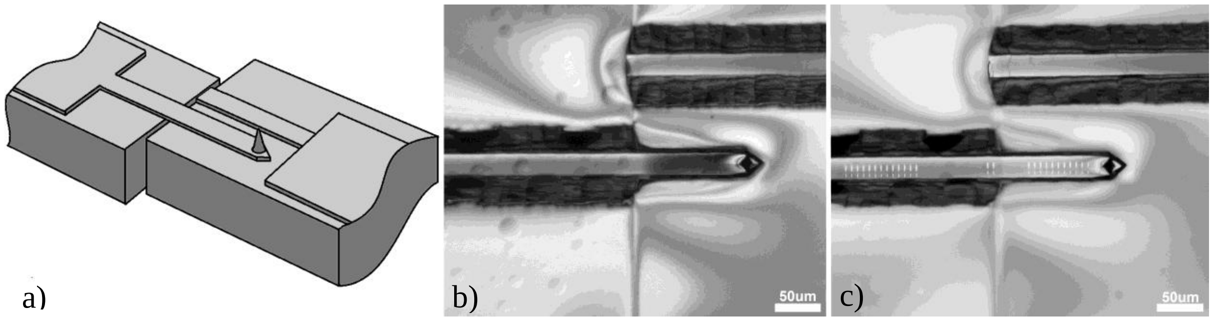

Fig.1: a) *Illustration scheme of the arrangement of chips during fabrication process. Optical microscope image of resist film after: b) spin-coating c) exposing and developing.*

The exposed pattern was a design of arrays of shorter and longer ellipses. Size of the shorter ones was designed to be 4 μm × 0,8 μm. Size of the longer ones was designed to be 7 μm × 1,5 μm. Ratio between length and width of ellipses was set to be enough for structure to be in a single domain magnetic state [12]. To reduce magnetic interaction between the neighboring ellipses within one array, the center-to-center distance was 6,5 μm. A higher number of ellipses were chosen to enhance mutual magnetic forces between arrays. The actual size of shorter ellipses after lift-off was 4,1 μm long and 0,93 μm wide and longer ones were 7,1 μm long and 1,65 μm wide. This is a little larger than was designed and it indicates the pattern was a little overexposed during EBL. The distance between arrays was 2,5 μm. The resist was developed for 1 min in a 1:3 solution of methyl-isobutyl-ketone (MIBK) and isopropyl alcohol (IPA). The cantilever with exposed and developed resist can be seen in Fig.1c). The deposition of permalloy $Ni_{80}Fe_{20}$ (Py) was done using thermal evaporation. Afterwards, resist lift-off was carried out in acetone for about half an hour. The chips were held together only by the resist layer, thus they detached from each other. At last, few seconds of ultrasonic agitation was necessary in order to completely lift-off the unwanted Py layer.

Finally, the prepared cantilever was cut by FIB milling. The sharp tip at the end of the cantilever was cut off and the cantilever was cut into halves. The milling process employed high energy Ga^+ column (30 kV) at the ion current of 0,3 nA. Figure 3c) shows the final cantilever sensor design.

3. Results and discussion

Generally, it is not trivial to scan free-standing structures (such as cantilevers) by means of tapping AFM mode. In inappropriate settings, the scanning cantilever (probe) could cause oscillations in the measured free standing structure that could introduce artefacts to image scans. Fig.2a) shows AFM image of the exposed PMMA resist after development. Clear scan without noise suggests that we have found out the optimal settings for the measurement. Fig.2b) shows a cross section of developed resist profile. Thickness of the resist on the area of the whole cantilever varied from ~70 to ~100 nm, which was sufficient for satisfactory lift-off.

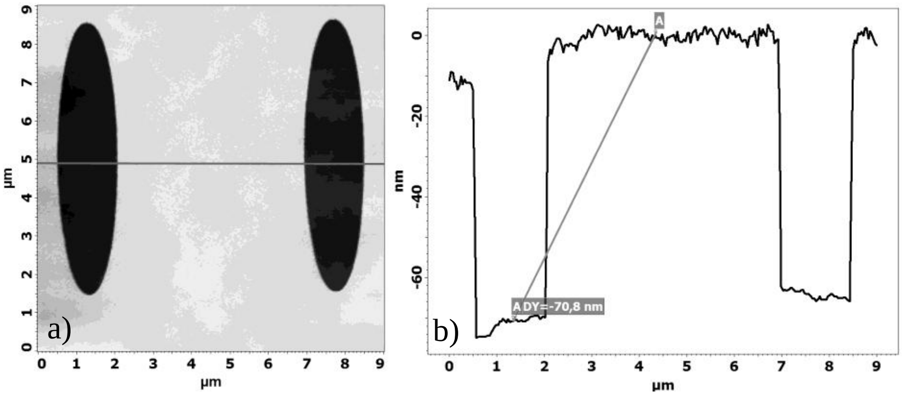

Fig.2: *AFM image of developed resist pattern (a) and representative cross section of developed resist profile (b).*

A series of scanning electron micrographs (SEM) of cantilever sensor is shown in Fig.3. Magnetic ellipses after Py deposition and lift-off are depicted in Fig.3a). Their edges are sharp and without fencing. Fig.3b) shows the whole cantilever with Py ellipses. As can be seen, there are two arrays of ellipses of different sizes, longer on the left and shorter on the right. Fig.3c) shows cantilever after being cut by FIB milling into halves.

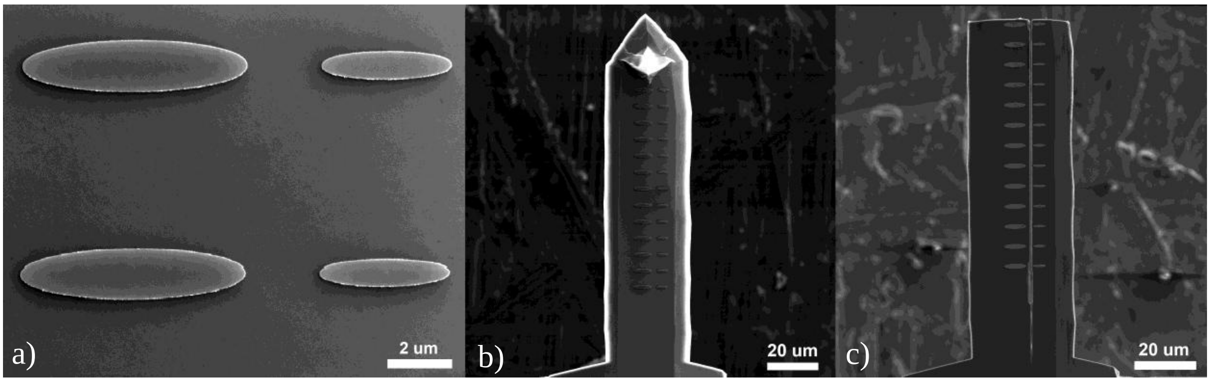

Fig.3: a) *Detail SEM of ellipses after lift-off.* b) *SEM of the cantilever after lift-off.* c) *SEM of the cantilever after being cut by FIB into halves.*

Chip with cantilevers, seen in Figure 3c) was then inserted in the AFM measuring head. The laser beam spot lied on both of the cantilevers. Resonance frequency peak of each cantilever was identified in NT-MDT Nova software (Fig.4). The concept of two arrays of longer and shorter ellipses was chosen in order to generate a coupling between cantilevers and change dominance of resonance frequencies; in other words, to change between single resonance peak and double peak in ideal case. In our experiment, this change was not observed. We assume it could be due to low sensitivity of sensor. In the future, we like to improve the sensitivity of the proposed sensor by following steps. First, the cantilever was probably too thick (~2 μm) hence it had high spring constant. Reduction of a cantilever thickness would lead to increase sensitivity [13], [14]. Second, distance between cantilevers was too large and mutual forces were too low. Minimalization of distance could increase coupling.

To demonstrate how the cantilever sensor should function, we performed series of magnetic force microscopy (MFM) scans of Py ellipses. To simplify the measurement, scans were carried out on ellipses prepared on planar surface out of the cantilever. The sample was put into an external in-plane magnetic field. Scans were then carried out in zero field, since magnetic field would interfere with MFM tip. Results are expected to be the same.

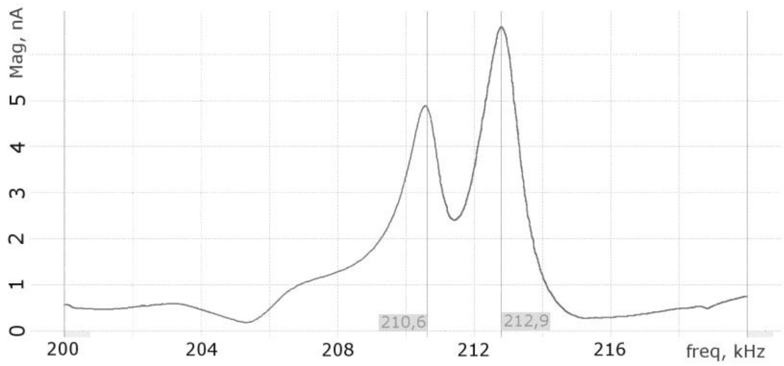

Fig.4: *Double resonant frequency peak of cantilever which was cut into halves.*

As can be seen in Fig.5, structures were in single domain state. Bright and dark regions represent positive and negative ends of the magnetic dipole. Fig.5a) shows a situation, when Py ellipses were magnetized in 100 mT field. The external magnetic field was strong enough to set orientation of magnetic dipoles into the same direction. In this case the coupling between the cantilevers would be attractive. That would ideally lead to oscillation of both cantilevers at the same frequency (cantilevers´ resonance peaks overlap).

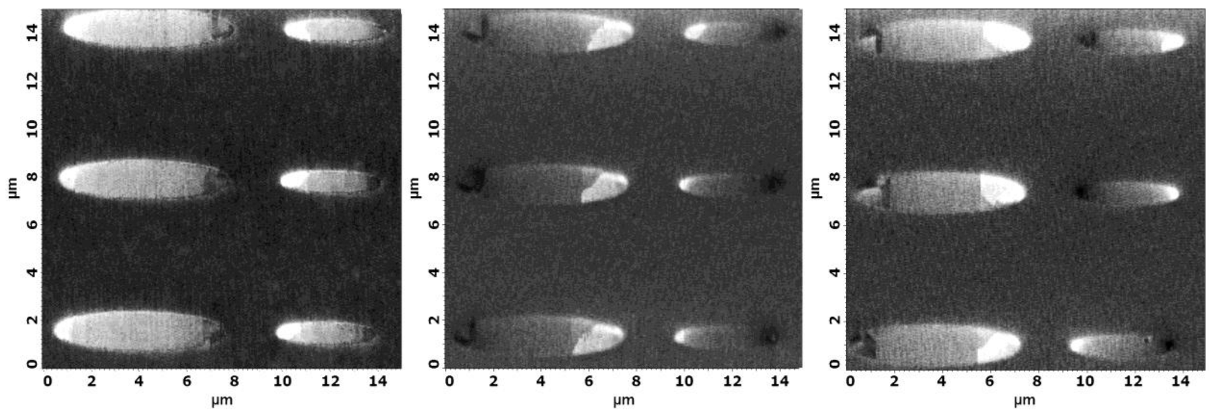

Fig.5: *MFM image of magnetic dipoles arranged in: a) the same direction b) the opposite directions c) the transient state.*

Next, the field was changed to opposite direction of -5 mT. This field was sufficient to convert only the array of longer ellipses into opposite directions (Fig.5b), which results from the basic principles of micromagnetism [15]. In this case the coupling between cantilevers would be repulsive. Each cantilever would oscillate on its own intrinsic frequency and the resonance peaks would be separating from each other. Fig.5c) shows a situation, when field was increased to value of -6 mT. This external magnetic field was not strong enough to arrange all the shorter ellipses to the opposite direction. In this transient state double frequency resonance peak would be identified. Mutual interactions between magnetic structures can be evaluated by shift of cantilevers´ resonance frequency peaks. A further increase of field would lead to completely converting all the shorter ellipses to the same direction. This feature can be utilized for magnetic sensor to study magnetic properties of the prepared ellipses (arbitrary magnetic structures in general). For example, mutual orientation of magnetic dipoles, whether dipoles are oriented in the exact or in the opposite directions, could be identified through location of resonance frequency peaks. Eventually, we would be able to measure the strength of field, which causes a change in magnetic orientation of the dipoles.

4. Conclusion

To summarize, in this work we proposed a magnetic cantilever sensor for study of magnetic structures. We fabricated magnetic microstructures on commercial AFM cantilever by means of advanced spin-coating process. We demonstrated our novel fabrication method by preparing arrays of magnetic permalloy ellipses on the cantilever. We showed the principle of functionality of proposed sensor by performing series of magnetic force microscopy measurement in external magnetic field.

In general, direct EBL lithography on a commercial cantilever is a very simple and fast method and has the potential capability to be applied for fabrication of any novel prototype cantilever based sensors and devices. The cantilever based sensor could be a suitable detection technique for the investigation of properties of magnetic structures of various shapes.

Acknowledgement

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