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Magnetic mesa structures fabricated by reactive ion etching with $CO/NH_3/Xe$ plasma chemistry for an all-silicon quantum computer

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Abstract
Micromachining of magnetic materials is becoming a crucial technology for future magnetic systems/devices such as high-density magnetic recording heads, high-density patterned media, magnetic quantum devices, and micro-magnetic smart systems. NiFe alloy, one of the typical ferromagnetic materials, can be deposited and fabricated using current thin film and micromachining technologies, and it has found various applications in microsensors, microactuators, and microsystems. In our recent work, $Ni_{45}Fe_{55}$ alloy with the highest saturation magnetic-flux density was selected as the micro-magnet for an all-silicon quantum computer. The micro-magnet was designed to create a large magnetic field gradient and to distinguish ^{29}Si nuclear spins arranged as chains in a ^{28}Si matrix with Larmor frequencies. This paper reports the micromachining of a $Ni_{45}Fe_{55}$ alloy mesa structure for an all-silicon quantum computer and the preliminary evaluation of its effectiveness using a magnetic force microscope (MFM) and a superconducting quantum interference device (SQUID).

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The use of magnetic materials, with particular emphasis on ferromagnetic materials, in data storage systems, solid-state sensors, actuators, and micro- and nano-systems is gaining increasing interest. Soft ferromagnetic materials have thus far found the most usage in the above applications. However, hard magnetic materials have unique advantages that are driving their integration with micro-electro-mechanical systems (MEMS).

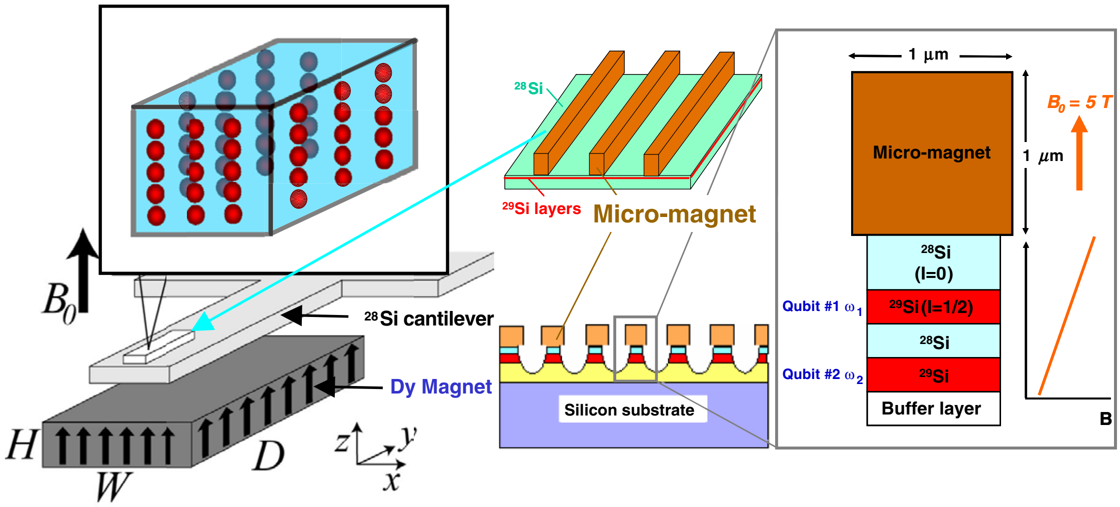

Figure 1. Schematic of an all-silicon quantum computer (left), and the design of a mesa structure with a micro-magnet (right).

The most commonly used ferromagnetic material is NiFe alloy (e.g., permalloy, which is typically 81% Ni and 19% Fe) due to its combination of relatively high saturation flux density, low hysteretic losses, and near zero magnetostriction. Well-developed deposition and under-development micromachining of the alloy also facilitate the integration with MEMS.

Micromachining of NiFe alloys is carried out mainly with ion milling, reactive ion etching (RIE), lift-off process, and electroplating [1].

As one of the two dry processes mentioned above, ion milling [2] is most widely used, but it is limited by problems such as sidewall deposition and lack of selectivity. There is a strong interest in the development of plasma etching processes for magnetic multilayer structures, and the creation of long and narrow (thin) submicro- or nano-structures of NiFe alloys for practical applications [1, 3]. There are two basic plasma chemistries that have been reported to etch NiFe alloys under high ion density conditions, namely Cl_2-based [3–5] and CO/NH$_3$ [1, 6]. Cl_2-based plasma offers good selectivity and anisotropy. However, the high temperature (greater than 200 °C) associated with the etching process is likely to cause problems for micro- and nano-systems, and limit the wafer throughput. This process also exhibits problems because of relatively non-volatile products and corrosion caused by residual chlorine. The use of non-corrosive CO/NH$_3$ plasma chemistry offers a high etch rate of up to 65 nm min^{-1}. The physically dominant nature of the etching process (physical sputtering rather than chemical reaction) may cause mask erosion, and thus lead to sloped sidewalls during deep etching [6]. This will limit the anisotropy to no better than 80°.

In our work, a newly developed CO/NH$_3$/Xe plasma chemistry [7] was used to micromachine $Ni_{45}Fe_{55}$ alloy to obtain mesa structures down to 500 nm. The fabricated mesa structures can be used as micro-magnets to create a large magnetic field gradient and to distinguish ^{29}Si nuclear spins arranged as chains in a ^{28}Si matrix with Larmor frequencies for an all-silicon quantum computer.

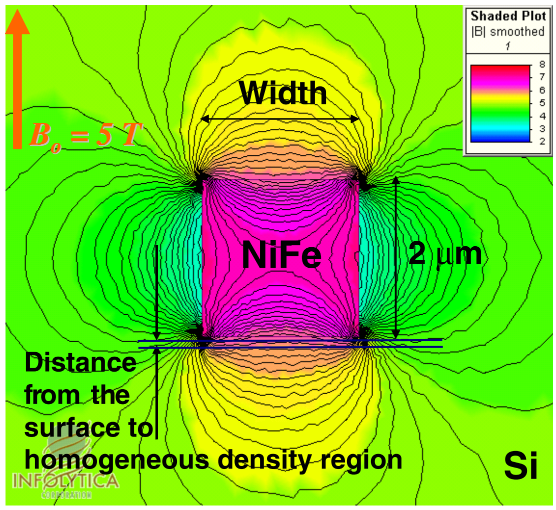

Figure 2. An example of simulation results, calculated with a finite element method using magnet Ver6.10 from Infolytica. The contour lines show plots that are the same magnetic flux density. The large magnet field gradient can be obtained along the static magnetic field and the homogeneous magnetic-flux density region exists at a distance about 150 nm from the micro-magnet surface.

2. Concept of an all-silicon quantum computer

Figure 1 shows the proposed solid-state implementation of a quantum computer [8]. The quantum computer is to be constructed entirely out of silicon, with no electrical gates or impurities. This is based on the phenomenon exhibited by stable nuclear isotopes of silicon: 95.33% of natural silicon is ^{28}Si or ^{30} Si, which are both spin 0, and 4.67% is ^{29}Si, which is spin 1/2 and is perfect for being the qubit. Qubits are thus ^{29}Si nuclear spins arranged as chains in a ^{28}Si matrix with Larmor frequencies, and are distinguished by a large magnetic field gradient created by a nearby micro-magnet. An ensemble of copies, orthogonal to the gradient direction, avoids the difficulty in measuring the nuclear spin of single atoms. The readout could be performed using a magnetic resonance force microscope (MRFM), which detects the oscillations of a thin ^{28}Si cantilever in which the rows of ^{29}Si atoms are embedded as shown in figure 1.

3. Design of mesa structure with NiFe alloy

In order to obtain a strong magnetic gradient with homogeneous magnetic-flux density, the design of a micro-magnet is carried out using Magnet Ver6.10 from Infolytica. The simulation was carried out with a two-dimensional micro-magnet superimposed by a large homogeneous field B_0 of $\sim$5 T, and the result is shown in figure 2. In the case of 2 μm thickness and 1 μm width, a strong gradient larger than 1.4 T μm^{-1}, which is necessary for detecting a qubit–qubit frequency difference of $\Delta\omega = 2\pi \times 2$ kHz [8], can be obtained at a distance about 150 nm from the upper or lower surface. A reasonable width between two neighbouring micro-magnets should be also considered to reduce mutual cancellation due to magnetic field superimposition. Considering the ensemble measurement of the spin-1/2 qubits within each chain, identical copies of the micro-magnet fabricated on one plane are therefore necessary. This is shown in figure 1 as an example of the micro-magnet design.

4. Micromachining of $Ni_{45}Fe_{55}$ alloy mesa structure

Since NiFe alloys can be both deposited and fabricated using current thin film technology and micromachining technology, a $Ni_{45}Fe_{55}$ alloy with the highest saturation magnetic-flux density was selected as the micro-magnet for the all-silicon quantum computer. The fabrication sequence is briefly described as follows. As shown in figure 3, a (100)-oriented silicon wafer was used as a starting material. A Ti layer of 200 nm thickness, a $Ni_{45}Fe_{55}$ thin film of 1 μm thickness, and a Ti layer of 8 nm thickness were deposited by ion beam sputtering using appropriate target materials. The top Ti layer was used as the mask material for etching $Ni_{45}Fe_{55}$ thin film, while the bottom Ti layer was used as an interlayer to improve the bonding strength between the Si(100) and the $Ni_{45}Fe_{55}$ thin film. The Ti pattern was defined by conventional photolithography with a UV cure and dry-etched by reactive ion etching (RIE) using SF_6 gas. The patterned Ti mask was then used to etch the $Ni_{45}Fe_{55}$ thin film in the same chamber using RIE with a mixture gas of CO, NH_3 and Xe. Finally, the Si(100) was dry-etched using a plasma etcher to obtain the mesa structure. The amount of undercut that occurs during the Si(100) etch step should be determined by an optimum cross-sectional width, that necessarily supports the micro-magnet and, at the same time, provides a homogeneous magnetic-flux density.

Figure 4 shows SEM images of the fabricated mesa structure of the $Ni_{45}Fe_{55}$ thin film. The cross-section of the micro-magnet is about 1.2 μm in width and 1 μm in height. A good anisotropy of about 80° was observed for the micro-magnet without sidewall deposition, corrosion and residues. It is difficult to achieve a much more ideal profile of close to a right angle (90°), because the top edges of the patterned Ti mask were slightly etched off through a physically dominant RIE process, because of the relatively lower etching selectivity ratio of $Ni_{45}Fe_{55}$ to Ti in this study. However, chemical

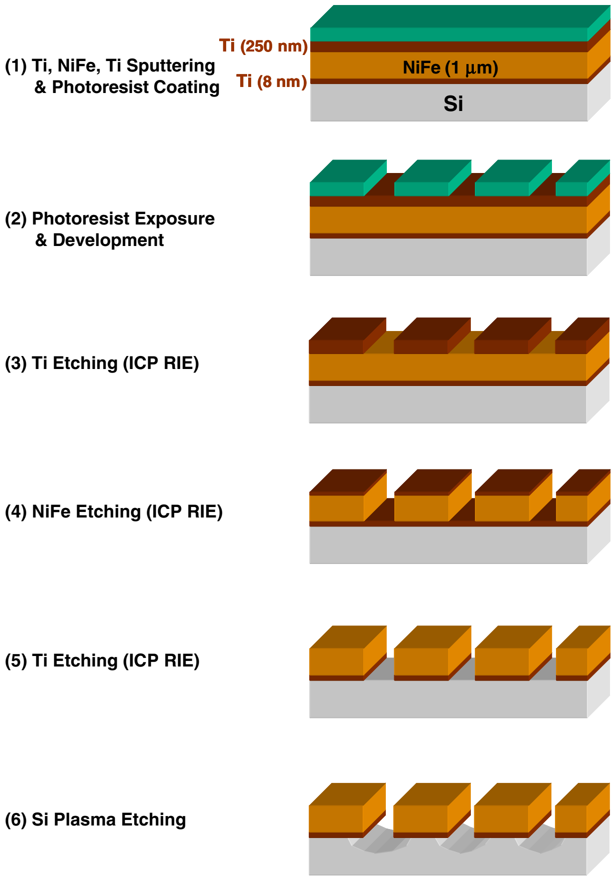

Figure 3. Fabrication sequence of a $Ni_{45}Fe_{55}$ alloy mesa structure, where $CO/NH_3/Xe$ plasma chemistry was applied to etching the $Ni_{45}Fe_{55}$ alloy.

reaction was also believed to play a part in the physically dominant RIE process, since an increment of 10% in the etching rate of $Ni_{45}Fe_{55}$ was observed when adding CO gas into NH_3 gas. The ion-assisted effect of Xe was further found to be helpful in improving the etching selectivity of CO/NH_3 gas.

5. Evaluation results

The imaging results obtained using a magnetic force microscope (MFM) qualitatively depict the magnetic field gradient at the corresponding area (see figure 5) of the fabricated $Ni_{45}Fe_{55}$ stripes. The evaluation result using a superconducting quantum interference device (SQUID) is shown in figure 6 and quantitatively indicates that the saturated magnetization is about 1.5 T when an external magnetic flux density of 5 T is applied. These results mean that there is no obvious deterioration in magnetization of the $Ni_{45}Fe_{55}$ alloy after $CO/NH_3/Xe$ plasma etching.

In future work, a nuclear magnetic resonance (NMR) measurement will be carried out to further verify the effectiveness of the large magnetic gradient created by the fabricated micro-magnet, which is crucially required for building an all-silicon quantum computer. A detectable Al layer of 5/2 nuclear spins could be applied to this NMR measurement [9]. The detailed consideration is to cover the fabricated micro-magnet with two Al layers separated by one

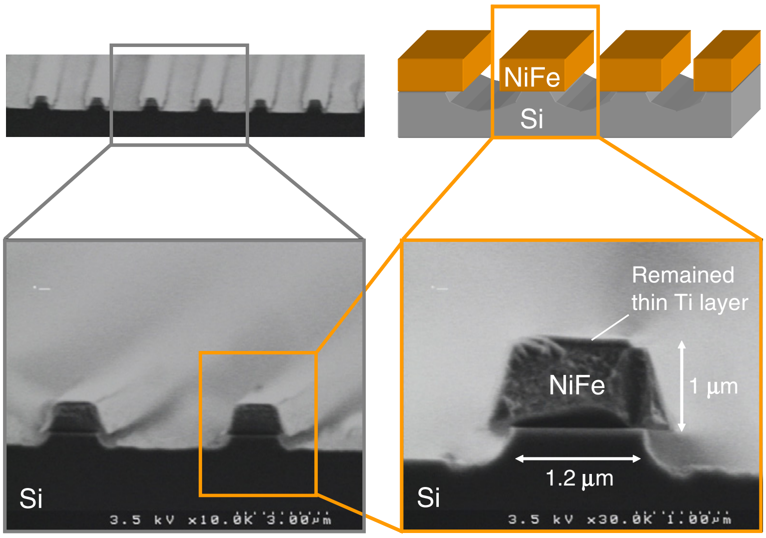

Figure 4. SEM images of the fabricated $Ni_{45}Fe_{55}$ alloy mesa structure; the cross-section of the micro-magnet is about 1.2 μm in width and 1 μm in height.

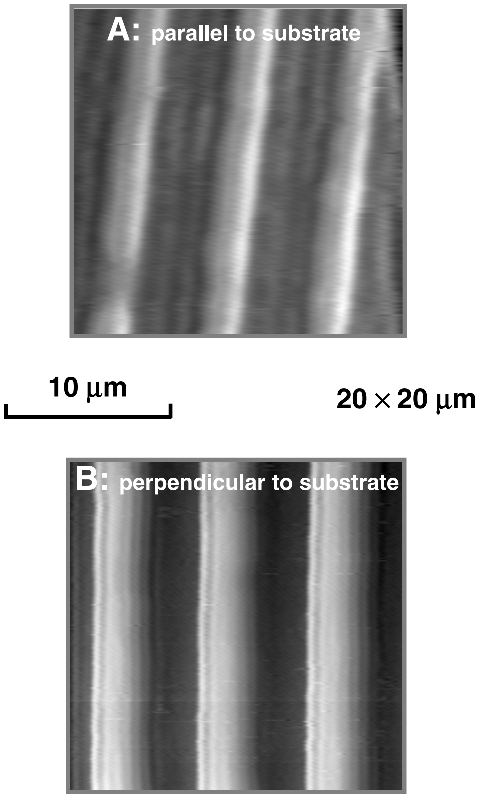

Figure 5. Magnetic gradient image results at the corresponding area observed by a magnetic force microscope (MFM). The MFM thin film tip was magnetized perpendicular to the sample. The observed results were obtained using the fabricated $Ni_{45}Fe_{55}$ alloy mesa structure magnetized either parallel (A) or perpendicular (B) to the Si substrate.

Ti layer. If a large magnetic field gradient is imposed on the two separated Al layers, two different NMR frequencies, proportional to the imposed magnet field gradient, should be thus detected.

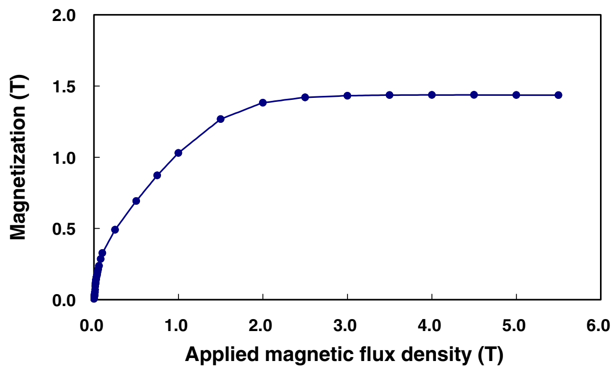

Figure 6. The saturated magnetization of about 1.5 T was measured by a superconducting quantum interference device (SQUID) when an external magnetic flux density of 5 T was applied.

6. Summary

A successful fabrication of a $Ni_{45}Fe_{55}$ alloy mesa structure was presented for an all-silicon quantum computer. Micro-magnet stripes with a good anisotropy of about 80° were achieved using reactive ion etching (RIE) with $CO/NH_3/Xe$ plasma chemistry. A saturated magnetization of about 1.5 T, showing no obvious deterioration, was measured with a superconducting quantum interference device (SQUID) for the fabricated $Ni_{45}Fe_{55}$ micro-magnet, when superposed by a B_0 of 5 T. These results represent good progress towards the physical realization of an all-silicon quantum computer.

Acknowledgments

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