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Fabrication of magnetic rings for high density memory devices

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Abstract

A new technique has been developed to fabricate magnetic ring elements. The technique is based on pre-patterning of silicon ring structures and subsequently epitaxial growth of copper–cobalt–copper sandwich film on top of silicon rings. In contrast to conventional methods of making magnetic elements, no damage to the magnetic layer structure is introduced by the patterning process. Unlike conventional magnetic structures, there are a number of challenges in patterning ring geometry by electron beam lithography and by reactive ion etching. Electron beam lithography process has been optimised for patterning ring structures of sub half micrometer dimension. Both conventional RIE and deep RIE techniques have been tried for transferring resist ring structure to silicon substrates. Large arrays of magnetic rings have been fabricated by the prepatterning techniques. Magnetic measurement by MOKE method has demonstrated the new onion state for magnetic switching, which is in agreement with computer simulation results.

Keywords: e-Beam lithography; RIE; MRAM; Magnetic data storate

1. Introduction

Magnetoresistive random access memory (MRAM) is promising to replace DRAM and SRAM or even disk drives as the next generation high density data storage device. The memory state in a MRAM is maintained not by external power supply but by the direction of magnetic moment. The high density is achieved by shrinking the size of magnetic element. In conventional small magnetic elements a uniform magnetization produces a large stray field, so there has to be a large spacing between elements to prevent magnetostatic coupling. One way to overcome this is to use the flux-closure vortex state. Unfortunately it is only stable in relatively large discs. Removing the highly energetic vortex core yields ring structures where the vortex state is also stable for small lateral dimensions. Furthermore, simulations and experimental observation of the magnetic rings have

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revealed a new magnetic state, termed 'onion state', which is of fast switching property and very stable [1,2]. Because the magnetic flux is confined in the ring, the inner diameter of the ring can be as small as 10 nm. In combination with vertically integrated CMOS circuitry, the ring element based MRAM promises the possibility of magnetic storage density up to 400 Gb/in^2, in contrast to the current level of 20 Gb/in^2.

To achieve very reproducible switching of the 'onion state', the magnetic ring should be as perfect as possible. Conventional techniques, such as physical evaporation and reactive ion etching cannot be applied for the ring element fabrication. Reactive ion etching of multilayer magnetic film is difficult, if not impossible, and damage to the film structure is inevitable. Thermal evaporation combined with lift-off process cannot produce the desired film crystalline structure. In this paper a new fabrication technique for making single crystalline magnetic ring elements is presented. The fabrication process is based on pre-patterning of silicon ring structures and subsequent epitaxial growth of copper–cobalt–copper sandwich film on top of silicon rings. Unlike integrated circuit patterns, the magnetic ring elements are much more difficult to make. There are a number of challenges in patterning ring geometry by electron beam lithography and by reactive ion etching. Both e-beam lithography and silicon etching processes have been optimised specifically for making the ring elements. Magnetic ring arrays of different dimensions have been successfully fabricated. Initial measurement has proved that the technique is able to produce individual magnetic ring despite the magnetic materials are deposited over the whole substrate. A new switching state, called 'onion' state which is predicted by theory for the magnetic ring elements, is confirmed.

2. Challenge of e-beam lithography

Electron beam lithography is known for having the highest resolution compared with other lithography methods. However, the exposure patterns normally encountered in e-beam lithography are either lines or dots. Using either PMMA resist or chemically amplified resists sub-50 nm lines and dots have been successfully delineated [3,4]. Ring geometry is different from lines and dots. The difficulty lies in the delineation of central hole in the ring. It is known that electron scatters in resist and substrate which is the cause of proximity effect. To illustrate the difficulty in pattering structures with a centrally unexposed area, Monte Carlo simulation of electron exposure and resist development have been carried out for a line pattern with a varying gap, using MOCASEL programme [5]. Fig. 1 shows the cross-section of resist profile of a 1 μm line with three different gap distances. The dashed line profile is the line with a 0.4 μm gap. The dash-dotted line profile has a 0.2 μm gap. The solid line profile is the line with a 0.1 μm gap. It is apparent that the smaller the central gap the more difficult to avoid exposure of the central area.

When it comes to the ring type pattern, it becomes worse because the central hole is surrounded by exposed area. Fig. 2(a)–(d) show a series of four ring patterns with different size of central holes. The rings were exposed by VB6-HR e-beam lithography system at 100 keV beam energy. The resist is AZPN114 negative tone chemically amplified resist from Clariant. The resist layer thickness is 0.8 μm. The 0.2 μm central hole in Fig. 2(d) has been partially exposed by electrons from surrounding exposed area, therefore, could not be fully developed. There are counter measures to overcome the electron proximity effect in e-beam lithography. Dedicated proximity correction software, such as CAPROX [6], have been developed which can automatically reallocate exposure dose to reduce the

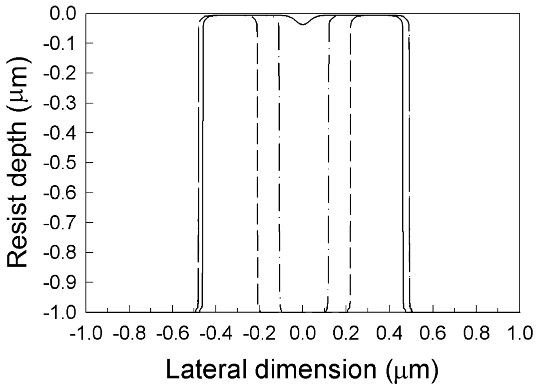


Fig. 1. Monte Carlo simulated resist cross-section for a 1 μm line with varying central gap (dashed line: 0.4 μm gap, dash-dotted line: 0.2 μm gap, solid line: 0.1 μm gap).

electron scattering effect. However, attempts to use CAPROX to correct the proximity effect in submicron ring patterns was not successful. The software could not fracture the ring pattern, therefore, could not reassign exposure dose at different parts of the ring. Without the help of proximity correction software, the only option left is to optimise exposure and resist process condition to minimise the proximity effect. High electron energy and thin layer resist have been used and resist development conditions have been optimised. Fig. 3(a) and (b) show the ring pattern with 200 and 100 nm inner holes.

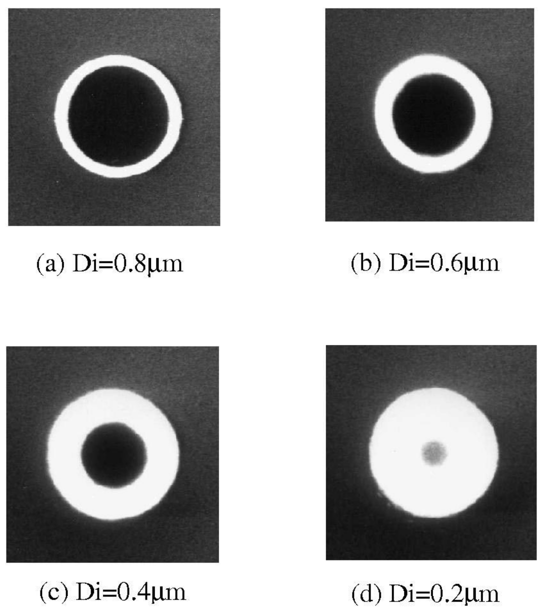
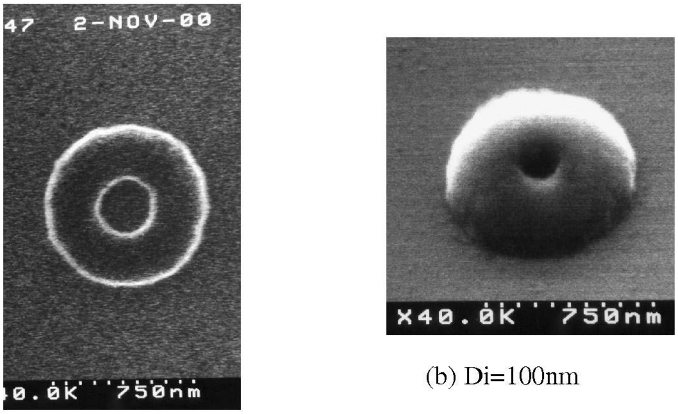


Fig. 2. Ring structure with 1 μm outer diameter and different inner diameters (D_i).



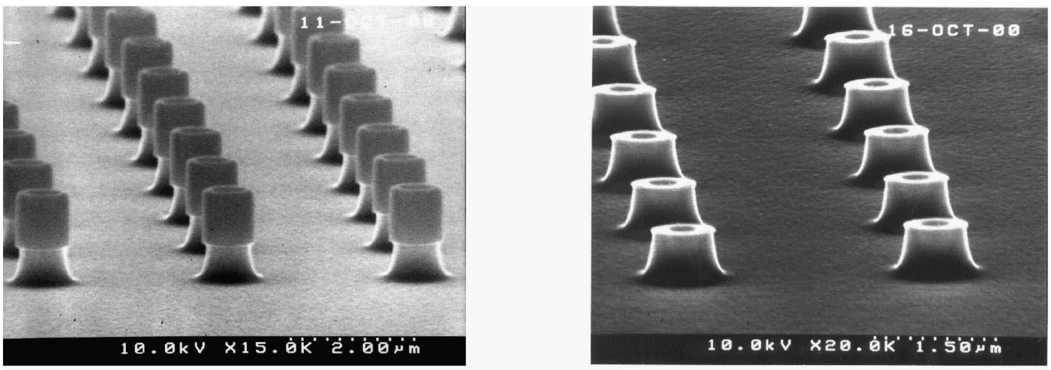
(a) Di=200nm

(b) Di=100nm

Fig. 3. Rings structures of different inner diameters (D_i) made from thinner (200 nm thickness) resist layer.

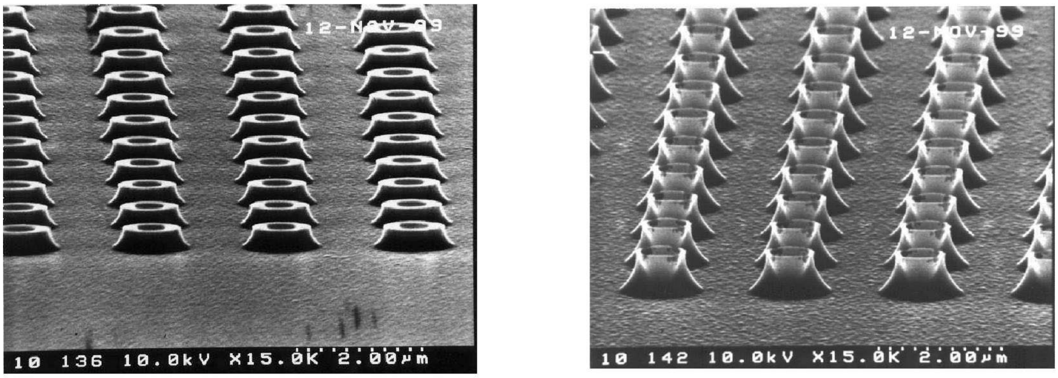
3. Challenge of silicon etching

The essence of the new technology for making magnetic ring elements is pre-patterning silicon rings then eptiaxially growing magnetic layers on top of the rings. The resist ring structure defined by e-beam lithography has to be transferred to silicon substrate. Because the magnetic layer is deposited all over the silicon substrate like a blanket, the silicon rings have to be high enough so that the magnetic layer on top of the rings are disconnected from the magnetic layer on the floor. Conventional reactive ion etch (RIE) of silicon using $SF_6 + O_2$ plasma is not 100% anisotropic. The etched ring structures are not perfectly vertical. Fig. 4(a) is an array of etched rings with resist masking layer still on top. Fig. 4(b) is the rings after removal of resist. Some degree of isotropic etching may have the advantage of controlling the ring width through control of etching time. Fig. 5(a) is an array of silicon



(a) (b)

Fig. 4. Conventional RIE of silicon rings (a) etched ring feature before removal of resist mask and (b) after removal of resist mask.



(a) (b)

Fig. 5. Etched ring features over different length of time: (a) 1.5 min and (b) 2 min.

rings after 1.5 min etching and Fig. 5(b) is the same rings after additional 2 min etching. The ring width becomes much narrower with the increased etching time.

The ideal profile for an etched silicon ring is to have an overhang at the top so that the deposited magnetic film at the top of rings will be discontinuous with the film at the bottom of the rings. Conventional RIE is extremely difficult to produce such profiles because of the undercut etching as shown in Fig. 5. There is a new deep silicon etching process which has been widely used for MEMS (micro-electro–mechanical system) structures. The deep silicon etching process, called Bosch process, is based on switching gases from etching to passivation in a short cycle [7]. Etching silicon by Bosch process always produces a slight overcut, which is ideal for depositing magnetic rings. The Bosch process, which so far has only been used for etching larger and deeper structures, has been adapted for etching ring structures of sub micrometer size and depth. By optimising the gas chopping cycle, it is possible to produce large array of silicon rings with near vertical profile, as shown in Fig. 6.

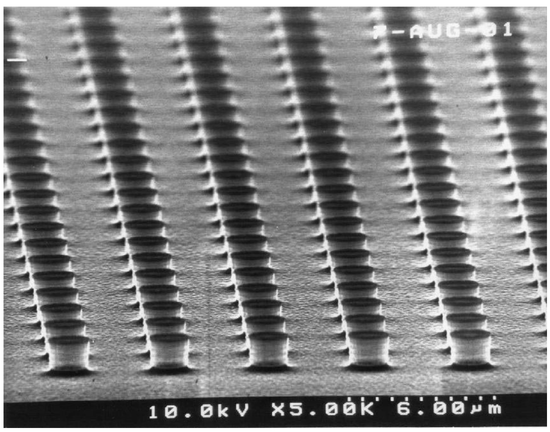


Fig. 6. Silicon ring structures by Bosch process.

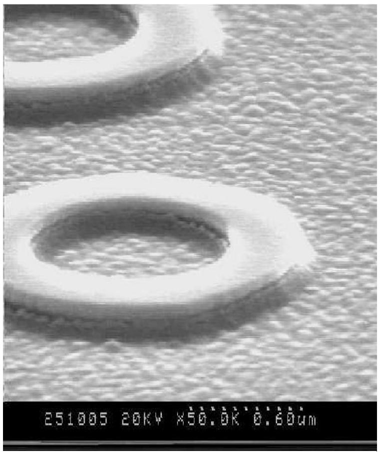


Fig. 7. Magnetic ring element after growth of Cu–Co–Cu layers on top of prepatterned silicon rings.

4. Formation of magnetic rings

After pre-patterning of silicon, a trilayer Cu(100)/Co(100)/Cu(100) on the Si(100) prepatterned rings in a UHV molecular-beam-epitaxy system (base pressure 3×10^{-10} mbar). The bottom copper layer of 65 nm serves as a buffer layer to ensure a high quality growth of fcc Co layer. The single crystal cobalt layer is 34 nm in thickness. The top copper layer of 2 nm is the capping layer to prevent the magnetic layer from oxidation. Fig. 7 is the SEM image of a ring after deposition of magnetic material. Although the epitaxial growth of magnetic material is everywhere on the substrate, the protrusion of prepatterned silicon rings ensures that magnetic film on top of the rings is disconnected from the substrate floor. Fig. 8 shows the detail of magnetic film on top of prepatterned structure and at the bottom of the trench. Preliminary measurement has confirmed that the magnetic rings made by

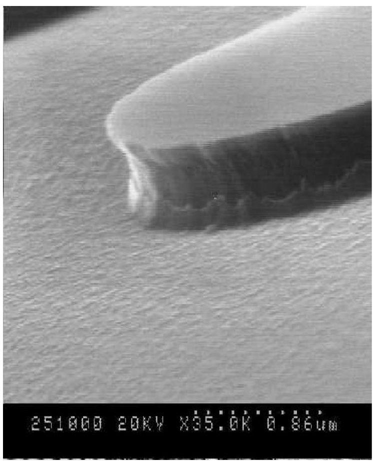


Fig. 8. Magnetic film grown by epitaxy on prepatterned silicon structures showing disconnection between the film on top of the structure and at the bottom of trench.

epitaxy growth on top of prepatterned silicon structure behave like individual magnetic rings, though the film is deposited in a blanket over the whole substrate. The detail of magnetic measurement has been reported elsewhere [1,2].

5. Summary

Magnetic ring elements have been fabricated by e-beam lithography, prepatterning of silicon and epitaxial growth of magnetic materials. Ring geometry with submicrometer dimension proves to be difficult to pattern by e-beam exposure due to proximity effect and the effect is impossible to correct by normal pattern fracturing and dose reallocation. Thin resist layer, high electron energy and optimised resist development process have been employed to pattern the ring structures. Both conventional RIE and deep RIE techniques have been tried for transferring resist ring structure to silicon substrates. The conventional RIE has the advantage of reducing ring width by controlling the etching time. The deep RIE process based on gas switching produced better profile suitable for magnetic film deposition. Large arrays of magnetic rings have been fabricated by the prepatterning techniques. Preliminary measurements have confirmed their magnetic properties.

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