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Magnetization Behavior of Co Nanodot Array

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We performed magnetic force microscopy (MFM) observation on array of Co dots in order to understand magnetic state and magnetization behavior of submicron sized Co dots patterned on GaMnAs bridge. MFM observations showed the magnetization reversal and processes of local magnetization of individual ferromagnetic Co nanodots. Magnetic state of Co dots either single domain or vortex is dependent on geometrical size and thickness. Transition from single domain to vortex state can be realized with MFM tip assisted local field. Magnetization reversal process takes place through sequential reversal of individual dots. Localized inhomogeneous magnetic field can be manipulated by controlling magnetic state of individual Co dot in the array structure.

Keywords : magnetic force microscopy, single domain, vortex

1. Introduction

Magnetization behavior and magnetic properties of ferromagnetic nanodot array structure have been an interesting topic in the field of magnetic information storage with ultra high density [1]. Recently, a lot of efforts have been exerted on the study of magnetization process of individual magnetic nanodot directly under either applied magnetic field or local field out of the magnetic force microscopy (MFM) probe. Either single domain or vortex state can be possible for ferromagnetic nanodot array. Single domain states (SD) with opposite directions of magnetization are possible in a small sized elliptical dot and vortex state (VS) is realized in a dot with the same geometrical size above critical length [2-5]. Single domain state is also possible in such ferromagnetic nanodots as a metastable state [6]. Different distribution of magnetic states of a few nanodots in array structure is a good source of an inhomogeneous local magnetic field. Magnitude of such inhomogeneous magnetic field is average of saturation magnetic moment M_s of individual ferromagnet dots and is determined by period of particles array. In addition, the magnetic field distribution can be varied by magnetizing or demagnetizing whole dot array or some of its parts.

Controllable inhomogeneous magnetic field induced by the dots has been used to manipulate the transport properties of superconductors [7-10] and Josephson junctions [11-13]. Recently, it was shown that inhomogeneous magnetic field produced by a ferromagnetic island acted as an effective potential that can efficiently trap spin polarized carriers in the system with giant Zeeman splitting [14].

One possibility to manipulate the magnetic state of ferromagnetic nanodots is magnetization reversal under the probe of magnetic force microscope. In this case, magnetic state of each selected element can be controlled by approaching the MFM probe to a specific dot individually. In such the way, we can create different distributions of magnetization in an array of ferromagnetic dots, which can be useful for various applications.

We fundamentally aimed at developing a novel hybrid device consisting of array of ferromagnetic nanodots patterned on the top of GaMnAs microbridge. This work focused mainly on the magnetization behavior and magnetization reversal of ferromagnetic dot array by using the MFM in order to understand the inhomogeneous magnetic field out of nanodot array which will be used to control the transport property of GaMnAs underneath ferromagnetic dot array for future study.

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2. Experimental Procedures

The standard UV photo lithography and Ar ion milling were used to fabricate 1 μm wide and 10 μm long microbridges with four contact probes from the GaMnAs diluted magnetic semiconductor film. The microbridge was designed to measure resistance change as a function of applied external field and induced local magnetic field from a chain of ferromagnetic nanodots to be formed on it. Prior to the fabrication of Co dots, surface of the microbridge was covered by 50 nm thick TaO insulating layer in order to prevent electrical contact between Co dots and GaMnAs. A chain of 300×700 nm^2 elliptical Co nanodots separated by 150 nm was patterned on the microbridge by the conventional electron beam lithography followed by lift-off process. For electron beam lithography, a commercial electron beam resist polymethyl methacrylate (PMMA) was chosen as an electron beam resist. A double layer (495 K/950 K) of PMMA was spin-coated on the substrate followed by baking at 180°C for 3 min. Undercut of 495 K affords easy lift-off after Co deposition. Electron beam patterning was carried out by using the scanning electron microscopy (SEM, JEOL 6500F) equipped with lithography system "Elphy Plus" (Raith GmbH). The electron beam was irradiated at accelerating voltage of 20 KV and area dose of 200 μC/cm^2. After exposure, the pattern was developed in a solution of methyl isobutyl ketone (MIBK): isoprophyl alcohol (IPA) 1:3 and rinsed in IPA for 1 min. Co film was deposited with an electron beam evaporator at a power of 50 KW prior to the lift-off process.

The distribution of remanent magnetization and processes of local magnetization process were observed using a multimode SPM "Solver-PRO" (NT-MDT). MFM measurements were performed in the noncontact constant height mode and the standard double pass tapping/lift mode. Standard Co-coated silicon cantilevers (MicroMash) magnetized along the tip axis prior to magnetic imaging were used in the MFM measurements.

3. Results and Discussion

Fig. 1 presents the scanning electron microscopy (SEM) and corresponding atomic force microscopy (AFM) images of a fabricated sample. Single array of Co dots was patterned on the top of GaMnAs microbridge. Controllable inhomogeneous magnetic field induced by the Co dots may lead to substantial change in transport property of GaMnAs as theoretically predicted by the literature [14]. It is important to study magnetic state and magnetization reversal behavior of patterned array of Co nanodots before we set out to measure the resistance of the sample as a function of inhomogeneous magnetic field.

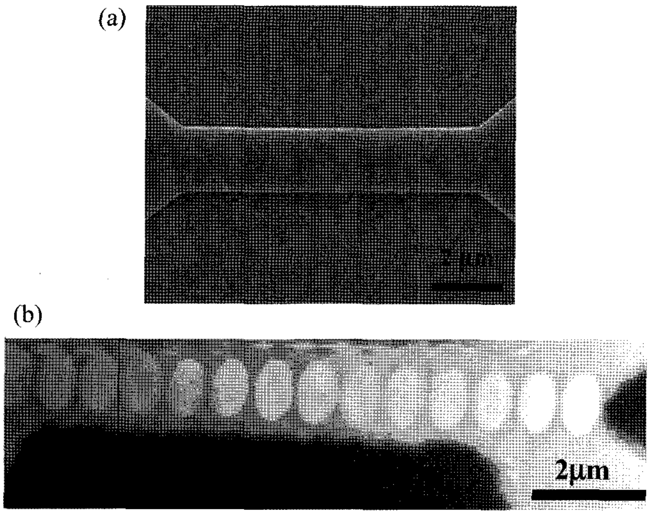
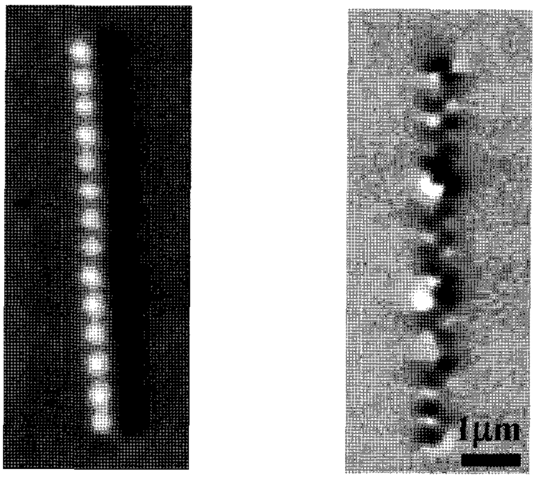


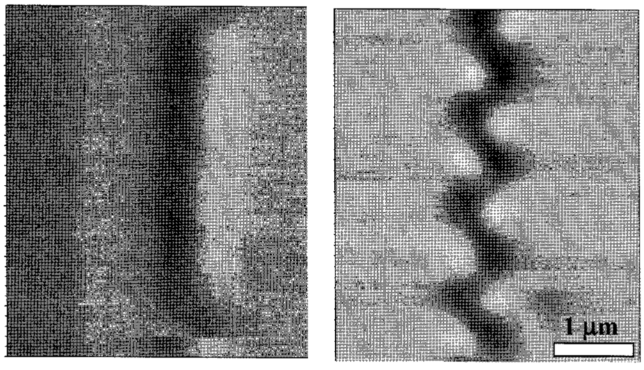
Fig. 1. SEM (a) and AFM (b) images of the fabricated sample. A chain of Co dots is patterned on GaMnAs microbridge.

MFM observation clearly shows the magnetic state of 20 nm thick elliptical Co nanodot array of which size is 300×700 nm^2. Long axis of elliptical Co dot is perpendicular to the bridge. Fig. 2(a) shows that all the dots form single domain states with the same moment orientation after saturation. Nevertheless the vortex states are also stable in the zero external field as shown in Fig. 2(b). Vortex states can be achieved with a help of MFM tip induced local field. For submicron Co dots, both single domain and vortex state are possible depending on the ratio of lateral size and thickness. Micromagnetic modeling and MFM investigations show that for the Co dots



(a) (B)

Fig. 2. MFM images of the chain of Co dots on the bridge. All of the Co dots are in the single domain state (a) and they are in the vortex states with the different directions of vorticity (b).



(a) (b)

Fig. 3. MFM images of chain of Co dots after magnetizing in the external field of 10 kOe parallel to long axis of elliptical Co dots (a) and after MFM tip induced antiferromagnetic ordering (b).

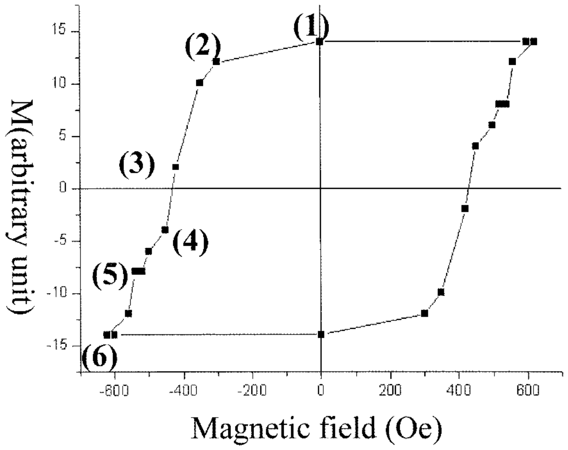
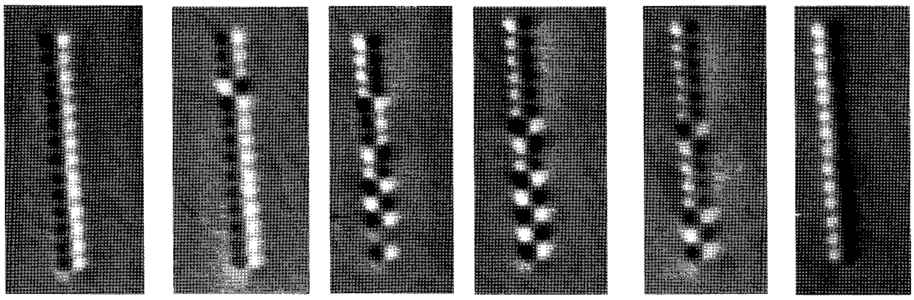


Fig. 4. The magnetisation curve of chain of Co dots at room temperature. The numbers indicates the point corresponding to the magnetic states of Co dots represented on the Fig. 5.

there is a characteristic thickness h^* about 25 nm, which separates the regimes of single domain and vortex stabilities [15, 16]. When the thickness of dot $h > h^*$, single domain is unstable while vortex becomes stable in the dots. Therefore, single domain is stable magnetic state of Co dots in the sample and vortex can be realized with the combined effects of the MFM tip's local stray field. We demonstrated the switching between single domain and vortex states happened on patterned array of Co dots. It means that inhomogeneous magnetic field can be controlled by manipulating the magnetic state of array of Co dots with MFM technique.

Magnetization reversal of single domain between right and left orientation is also very intriguing issue in controlling local magnetic field configuration in the arrays of Co dots. The distribution of magnetic moment of dots in the chain strongly depends on the interdot distance. For the chains with separation less than 100 nm, we observed antiferromagnetic ordering of moments of dots in the remanent state. [17] It is a result of magnetostatic interaction between dots. This interaction leads to unusual behavior of the system. Here, we conducted the experiments with dots, which have lateral sizes of 300×150 nm^2, 10 nm in thickness separated by 150 nm. After magnetizing in the external field 10 kOe in direction to long axis, this chain has ferromagnetic order as shown in MFM image (Fig. 3(a)). In this state chain of dots have finite averaged magnetic field.

The MFM probe induced antiferromagnetic ordering of this chain was performed in the constant height mode. The height of scanning was reduced over selected dots until they change direction of magnetic moment to opposite. The distribution of local magnetic moments in dots after probe induced antiferromagnetic ordering can be seen in Fig. 3(b). In this state averaged magnetic field of dots row is equal to zero. Field switch on and off effects were clearly seen in the dependence of critical supercurrent of coplanar Josephson junction with ferromagnetic dots upon external magnetic field. [11] The same principle can be used to control magnetic field in the hybrid device where chain of ferromagnetic dots are patterned on GaMnAs



(1) (2) (3) (4) (5) (6)

Fig. 5. MFM images of chain of Co dots showing sequence of the magnetization reversal of individual Co dot during magnetisation reversal.

microbridge by means switching of magnetic moment of dots grown over the spin current channels.

For better understanding of the magnetization reversal process of individual Co dots on the GaMnAs bridge, we obtained magnetisation curve of the chain consisting of 14 Co dots at room temperature and found out hysteretic behaviour of the magnetisation while magnetising along long axis of them. Fig. 4 shows the magnetization curve of the chain of Co dots and Fig. 5 shows series of MFM images of Co dots corresponding to each point on the curve marked as a number in Fig. 4. As already shown in Fig. 2(a), all dots have single domain state with the same moment orientation after saturation. Single domain states are still stable at remanent state (point 1) and as applying negative magnetic field, one Co dot reversed to opposite direction. (point 2) Rest of Co dots gradually reversed to left orientation as increasing the negative magnetic field subsequently. When the number of reversed Co dots exceeds the half, magnetization also changes to the reverse. The hysteric behaviour of the chain of Co dots matched well with individual magnetization reversal of dots. On the negative saturation (point 6), all dots changed their moment orientation, which is proved by their MFM contrasts contrary to those of point 1. The investigation confirms the fact that magnetization reversal process takes place through sequential reversal of individual dots.

Through MFM observation of Co dot array patterned on GaMnAs, we understand magnetic state of Co dots and learn how to control magnetic state by MFM tip assisted local field in order to produce controllable inhomogeneous magnetic field which may lead to substantial change in transport properties of GaMnAs bridge underneath a chain of Co dots.

4. Conclusion

In conclusion, MFM observation on the chain of Co dots patterned on GaMnAs microbridge was carried out for understanding magnetic state and magnetization behavior of submicron sized Co dot array. Magnetic state of Co dots is dependent on spatial size and thickness. Single domain state can be switched to vortex state with a MFM tip assisted local field. MFM technique is found to be a useful method to control individual magnetic state of different objects. For a chain of Co dots with single domain state, magnetization reversal process takes place through the sequencial reversal of individual dots. Inhomogeneous magnetic field can be manipulated by controlling magnetic state of individual Co dot in the array structure.

Acknowledgements

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