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13. ABSTRACT *(Maximum 200 words)*

We have (1) developed high-resolution magnetic force microscopy (including a new MFM tip structure and calibration ring) and used it to investigate patterned magnetic structures; (2) found that the in-plan magnetoresistance of nanoscale squares is over 600 % due to the well-defined magnetic domain structures induced by the small size and shape anisotropy; and (3) observed spin-valve effects in ferromagnetic/semiconductor/ferromagnetic diodes.

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Enclosure 1

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ULTRA-HIGH DENSITY ARTIFICIAL-STRUCTURED NANOMAGNETIC ARRAYS AND DEVICES

FINAL REPORT

STEPHEN Y. CHOU

AUGUST 26, 1996

OFFICE OF NAVAL RESEARCH

CONTRACT/GRANT NUMBER N/N00014-93-1-0256

DEPARTMENT OF ELECTRICAL ENGINEERING
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I. Objective

The three-year research aimed at experimentally investigating new nanoscale magnetic arrays and devices, that are fabricated using nanotechnology.

II. Summary of Major Accomplishments

2.1 Magnetic Force Microscopy

As the first step of this research program, we have successfully constructed a high resolution magnetic force microscope (MFM)[1-2]. Based on a commercial atmosphere atomic force microscope (AFM) made by Park Scientific, we built a vacuum chamber (for high-Q), re-engineered the electronics and mechanics parts, modified the measurement schemes, and rewrote a portion of the computer codes. The MFM has a high sensitivity of a detectable magnetic force gradient as small as 10^{-8} N/m and has a high spatial resolution of 40 nm.

Using the system, we investigated magnetic properties of various patterned magnetic structures. We also developed a new MFM tip that has a magnetic spike on an ordinary AFM tip and offers higher resolution and smaller stray field than that of a conventional MFM tip. Furthermore, we developed a micro-size current ring which can precisely calibrate the magnetic moments of a MFM tip.

2.2. Over 600 % Change in In-Plane-Hall Magnetoresistance of Micronscale Nickel Thin-Film Squares

We found that as the size of a ferromagnetic thin film square is reduced into micron scale, the magnetic domains in the square will change from random to ordered[5]. This produces a profound effect on the MR change. For 2-μm square, the MR change, defined as $(R_{max}-R_{min})/R_{min}$, was found to be 610 %, where the current (*I*) is driven across the two leads along a diagonal direction of a rectangle and the voltage (*V*) is measured at the other pair of leads in the other diagonal direction to obtain the resistance (*V/I*). An in-plane magnetic field is applied in parallel to a side of the rectangle.

The MR change was found to depend on the square width, having a maximum at 2-μm width. Larger or smaller than this width, the MR change decreases. Furthermore, it is also found that the MR change also depends on the shape symmetry of the rectangles, having a maximum at symmetrical shape.

Magnetic force microscopy (MFM) was used to study the magnetic domain structures of the samples. It is found that in the 2-μm squares where the in-plane-Hall MR change is over 600 %, the MFM image consists of four well-defined symmetrical closure domains with an identical shape and four 90° domain walls. For the squares of a 1-μm width or less, the MFM image shows a single domain with a north pole and a south pole and with the magnetization direction in the diagonal of the square. For the squares of 3-μm width, the MFM image shows a chaotic domain pattern. The MFM study indicated that the large MR change can be attributed to the well-defined symmetrical magnetic domain formation in the micronscale Ni film.

2.3. Spin Valve Effects in Nickel/Silicon/Nickel Diodes

We fabricated and investigated ferromagnetic/semiconductor/ferromagnetic (FM/S/FM) diodes[6]. Each diode has two sets of interdigited nanofingers on top of a silicon substrate . Each set of fingers has a 35-nm thickness, 14 mm length, but different finger width (75 nm for one set and 150 nm for the other) and therefore different switching fields (i.e. each set switches at different magnetic fields). Magnetoresistance showed spin valve behavior (e.g. As the magnetic field scans from -600 Oe, the resistance sharply increases around -50 Oe, stays flat, and then sharply decreases around 380 Oe; the effect is similar in reverse scanning). The amplitude of MR change was typically 0.3~0.6% at room temperature but increased somewhat with lower temperatures. Furthermore, such MR changes were not observed for the FM/S/FM diodes with identical finger widths.

The above observed effect was explained using a spin-valve model: the resistance depends on the relative spin orientation of the two FM finger sets. Since the two finger sets have different switching fields, at a certain magnetic field range, the two sets of fingers have an anti-parallel spin orientation, and therefore a higher resistance. In the other region, the spins of two finger sets are parallel to each other which results in a lower resistance.

The finger spacing of the devices is typically 500 nm; hence, tunneling is very unlikely. In fact, the current is dominated by the thermionic emission across the Schottky barrier. One explanation for the spin valve effects is the spin-dependent scattering at the interface and inside of the ferromagnetic fingers. Other models are being considered and further investigation is underway.

III. List of Publications

[1] S. Y. Chou, M. S. Wei, and P. B. Fischer, "An Ultra-high Resolution Single-Domain Magnetic Force Microscope Tip Fabricated Using Nanolithography", *IEEE Trans. on Magnetics*, **30**(6), 4485-4487, Nov.,1994.

[2] M. S. Wei and S. Y. Chou, "Size Effects on Switching Field of Isolated and Interactive Arrays of Nanoscale Single-Domain Ni bars Fabricated Using Electron-Beam Nanolithography, *J. Appl. Phys.* **76**(10), 6679-6681, 1994.

[3] S. Y. Chou, M. S. Wei, P. R. Krauss, and P. B. Fischer, "Study of Nanoscale Magnetic Structures Fabricated Using Lithography and Quantum Magnetic Disk", *J. Vac. Sci. and Tech.*, **B12**(6), 3695-3698,1994.

[4] P. R. Krauss, P. B.Fischer, S. Y. Chou, "Fabrication of Single-Domain Magnetic Pillar Array of 35 nm Diameter and 65 Gbits/in^2 Density", *J. Vac. Sci. and Tech.*, **12**(6),3639-3642, 1994.

[5] Y.Q. Jia, Rick C. Shi, and S.Y. Chou, "Spin-Valve Effects in Transport Perpendicular to Nickel/Silicon/Nickel Diodes," *IEEE Trans Magnetics* 32(**5**) 4707 1996.

[6] Y.Q. Jia, R.C. Shi, L. Kong and S.Y. Chou, "Effects of Sample Size and Field Orientation on Pseudo-Hall Voltage in Micronscale Nickel Thin-Film Squares," *J. of Appl. Physics,* **81**(8) 15 April 1997.

IV. List of Personnel Participating The Scientific Project

Principal Investigator: Professor Stephen Chou

Post-Doctoral: Linshu Kong and Vic Jia

Students: Andrew Stutart, Mark Wei, and Rick Shi

V. Advanced Degrees Awarded to Personnel on the Project

M.S. Degree:

Andrew Stutart (MEEE1994)

Mark Wei (MSEE1995)

VI. Invention Disclosure

None

An Ultra-high Resolution Single-domain Magnetic Force Microscope Tip Fabricated Using Nanolithography

Ref - 1

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Abstract **- An ultra-high resolution MFM tip is proposed and demonstrated. The tip consists of a ~30 nm thick ferromagnetic film coated on a non-magnetic pillar that has a diameter of 150 nm, a length over 1.5 μm and a sharp end of a 10 nm radius. The pillar was fabricated on the apex of a commercial scanning force microscope tip using electron beam lithography. The ferromagnetic films were coated only on one side of the pillar but not on the rest of the tip. Therefore, the tip has a trough shape and a tapered end with a tip radius of ~10 nm. The ferromagnetic trough is single-domain because of its nanoscale size and shape anisotropy. Compared to conventional Ni wire tips, the new tips have a much smaller magnetic charge distribution at the end of the tip, thus offering better imaging resolution. Furthermore, they have a lower stray field, thus making them well suited to measuring soft magnetic materials.**

I. INTRODUCTION

The magnetic force microscope (MFM) tip is one of the most important elements in determining the resolution and sensitivity of a MFM [1-4]. Previously, sharpened Ni wires [1] and magnetically coated atomic force microscope tips [5] have been used as MFM tips. Both kinds of tips suffer from several drawbacks. First, these tips are large in area, and therefore consist of multiple magnetic domains and have a broad distribution of magnetic charge that results in poor spatial resolution. Second, the tips have a sizable magnetic charge that can alter the magnetic properties of the magnetic material under inspection. To avoid such interference, the tip has to be kept rather far away from the sample surface, drastically reducing the MFM's sensitivity.

Here we propose and demonstrate a new, ultra-small, single-domain MFM tip that has very small distribution and magnitude of magnetic charges, and therefore offers a resolution many times greater than other MFM tips.

II. TIP STRUCTURES

The novel MFM tip consists of a thin, narrow, but rather long magnetic spike on a nonmagnetic conventional scanning force microscope (SFM) tip.[6] The width and thickness of the magnetic spike are typically a few nanometers and its length is about 1 μm. The dimensions of the magnetic spike are so chosen that the spike is a single magnetic domain and therefore the tip is referred as single-domain spike (SMS) tip. The MFM tip has two important advantages. First, due to the single-domain and sharpness of the tip, the magnetic charge is concentrated in a very small area at the end of the tip therefore it offers higher resolution. Second, due to the small magnetic charge, it is less likely to alter the magnetic properties of the sample.

In this paper we present one embodiment of such a SMS tip, its fabrication technology, and evaluate its performance. The SMS tip consists of a long non-magnetic spike of nanoscale diameter and a ferromagnetic film that covers only part of the pillar but not the rest of the tip. Therefore, the ferromagnetic portion of the SMS tip has a trough shape with a 10 nm end radius.

III. TIP FABRICATION

The SMS tip fabrication process consists of two main steps (Fig. 1). (1) The non-magnetic pillar was fabricated by contamination electron beam lithography on top of the pyramid of a commercial scanning force microscope (SFM) tip. (2) Ferromagnetic materials, such as nickel or cobalt, were coated on one side of the pillar. In the first step, SFM cantilevers were first sputter coated with 20 nm of gold to prevent charging during the electron beam contamination lithography and to facilitate subsequent focusing on the apex. The tips were then mounted and inserted into an electron beam lithography system with a diffusion pump vacuum system and a tungsten filament gun. A contamination pillar was then grown on the apex by exposing the tip in spot mode for a specified length of time. Growth is due to electron beam assisted molecular deposition onto the cantilever surface. The deposited material was not intentionally introduced, but originates primarily from the background of the lithography system's vacuum chamber and from the sample surface itself. Similar contamination deposits have been shown to be mainly composed of carbon and oxygen.[7]

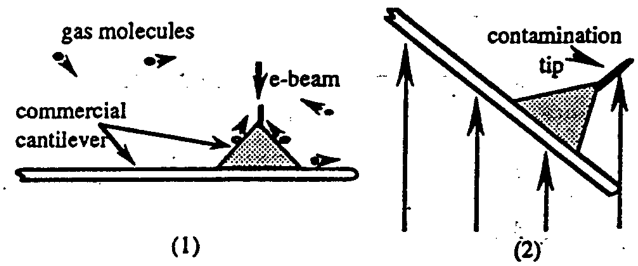

Fig. 1. Schematic of the fabrication process.

The tip growth process was investigated and optimized to produce long but narrow pillars with small tip radii that are desirable for high resolution MFM tips. We found that the accelerating voltage and beam current were the most significant parameters in the growth process. It was found that the growth rate would increase with increase of accelerating voltage or decrease of beam current. Figure 2 shows the tip length versus the exposure time at three

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Size effects on switching field of isolated and interactive arrays of nanoscale single-domain Ni bars fabricated using electron-beam nanolithography

Ref-2

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Isolated nanoscale Ni bars with a length of 1 μm, a width from 15 to 300 nm, and interactive bar arrays with a spacing from 200 to 600 nm were fabricated using electron-beam lithography and were studied using magnetic force microscopy. The study showed that the virgin magnetic state of bars with a width smaller than 150 nm was single domain and otherwise multidomain. It also showed that the switching field of isolated bars initially increases with decreasing bar width, then reaches a maximum switching field of 740 Oe at a width of 55 nm, and afterwards decreases with further bar width reduction. Furthermore, it was found that the switching field of the interactive bars decreases almost linearly with reduction of the spacing between the bars.

I. INTRODUCTION

Understanding the behavior of a single domain magnetic particle and the interaction between the particles is very important, because these particles are the basic constituents of many magnetic recording materials. However, previously most experimental studies of magnetic particles were made in an ensemble of such particles and the properties of a single particle were inferred only through extrapolation. Due to large variation in particle dimensions, randomness of magnetization and unavoidable interaction, detailed information about single particles and their interaction is smeared out.

Due to advance in nanofabrication technology, now it is possible to nanoscale magnetic particle arrays with precise sizes, shapes, and spacing. This opens up new opportunities to understand the fundamentals of micromagnetics and develop new magnetic materials. Recently, the first reported study of nanoscale permalloy bars fabricated using electron beam lithography was carried out by a joint team from the University of California at San Diego and IBM.[1,2] In that study, isolated bars had a fixed length of 1 μm and a fixed width of 133 nm and interactive bar arrays had a fixed spacing with the strongest coupling along the bars' long axis.

In this article, we present the fabrication and investigation of isolated Ni bars with a width varying from 15 to 300 nm and interactive Ni bar arrays with a spacing varying from 200 to 600 nm with the strongest coupling in the bars' short axis. Furthermore, we report and discuss the effects of bar width and spacing on the switching field of these isolated and interactive bars.

II. FABRICATION OF NANOMAGNETIC BAR ARRAYS

The isolated and interactive nanomagnetic nickel bars were fabricated using electron-beam nanolithography and a lift off process. In the fabrication, a resist, polymethyl methacralate (PMMA), was first spun onto a silicon substrate. A high resolution electron beam lithography system with a beam diameter of 4 nm was used to expose bar arrays in the PMMA. The exposed PMMA was developed in a cellosolve and methanol solution to form a resist template on the substrate. A nickel film, 35 nm thick, was evaporated onto the entire sample. In the lift off, the sample was submersed in acetone which dissolved the PMMA template and lifted off the nickel on its surface, but not the nickel on the substrate. After fabrication, bar widths were determined using a scanning electron microscope (SEM) and the bar width presented here is the measured bar width.

For isolated bars, the bar length was fixed at 1 μm, but the bar width varied from 15 to 300 nm. The spacing between isolated bars is 10 μm. Figure 1 shows a scanning electron micrograph of a Ni bar with a 15 nm width.

For interactive bar arrays, the bar width and length were fixed at 100 nm and 1 μm, respectively. The spacing between bars along the long axis is 2 μm, but the spacing between the bars along the short axis varies from 200 to 600 nm. Therefore the interaction between bars is primarily along the short axis, and the bar arrays can be regarded as isolated rows of one dimensional interactive arrays. This is very different from that in Ref. 1 where the bars were coupled primarily along the long axis. To illustrate the fabrication resolution

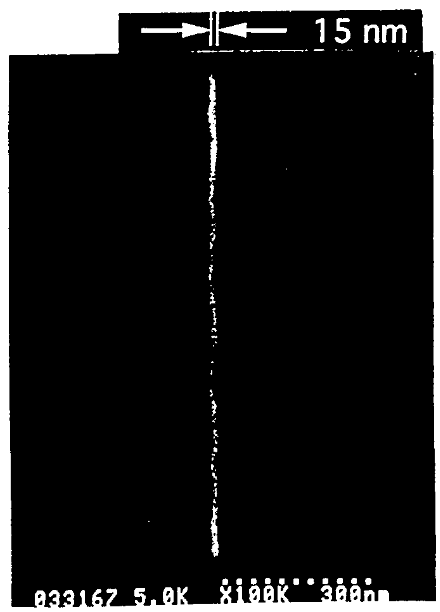

FIG. 1. SEM image of a high aspect ratio isolated Ni bar that is 1 μm long and 15 nm wide.

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Study of nanoscale magnetic structures fabricated using electron-beam lithography and quantum magnetic disk

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Ref-3

(Received 22 June 1994; accepted 31 August 1994)

Two types of nanoscale single-domain magnetic structures were fabricated using e-beam nanolithography and were studied using magnetic force microscopy. The first structure is the isolated and interactive arrays of Ni bars on silicon that are 35 nm thick, 1 μm long, and have widths ranging from 15 to 200 nm and spacings ranging from 200 to 600 nm. The second structure is an array of Ni pillars on silicon that have a uniform diameter of 35 nm, a height of 120 nm, and a density of 65 Gbits/in^2—over two orders of magnitude greater than the state-of-the-art magnetic storage density. It was found that the magnetic properties of these structures can be controlled by engineering their size and spacing. When the bar width is smaller than 150 nm, the bars become single magnetic domain. As the width of the isolated bars decreased from 200 to 55 nm, the magnetic field needed to switch the magnetization of these bars increased monotonically from 100 to 740 Oe which is the highest field reported for Ni. However, further reduction of bar width led the switching field to decrease due to thermal effect. Furthermore, it was found that as the bar spacings become smaller, the interaction between the bars will reduce the switching field. Finally, based on the artificially patterned single-domain magnetic structures, we propose a new paradigm for ultra-high-density magnetic recording media: quantum magnetic disk.

I. INTRODUCTION

Coercivity, coercive squareness, and many other magnetic properties of a magnetic thin film strongly depend upon the geometric factors of the magnetic grains in the film such as the grain size and anisotropy, the grain magnetization orientation, and the spacing between the grains. Generally, however, in a conventional as-deposited magnetic film the magnetic grains have a broad distribution of the grain size, anisotropy, spacing, and nearly random magnetization. Therefore the conventional magnetic media have a large variation of local magnetic properties, making them unsuitable for ultra-high-density recording and hard to compare with theory. To develop new materials for ultrahigh magnetic recording and to obtain a better understanding of magnetic behavior of a material, many methods have been attempted in order to control the geometric factors of magnetic grains in a thin film. The approaches include control of film deposition conditions, alloying, epitaxial growth on crystal substrates, introduction of stacking faults, and insertion of nonmagnetic material between the magnetic grains. However, none of these approaches offers precise control of the geometric factors.

As nanofabrication technology advances, it is now possible to precisely control the geometrical factors of magnetic grains in a thin film using nanolithography. These nanolithographically defined magnetic materials open up new opportunities to engineer novel magnetic materials and understand the fundamentals of magnetics. Recently, a joint team from the University of California at San Diego and IBM studied nanoscale permalloy bars fabricated using electron-beam lithography.[1,2] In that study, isolated bars had a fixed length of 1 μm and a fixed width of 133 nm; interactive bar arrays had a fixed spacing with the strongest coupling along the bars' long axis.

In this article, we present the investigation of isolated Ni bars with a width varying from 15 to 200 nm, and interactive Ni bar arrays with a spacing varying from 200 to 600 nm with the strongest coupling in the bars' short axis. We will report the effects of bar width and spacing on the switching field of these isolated and interactive bars. We will also report the study of arrays of Ni pillars that have a uniform diameter of 35 nm, a height of 120 nm, and a density of 65 Gbits/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. Furthermore, we will discuss a new paradigm for ultra-high-density magnetic recording based on the lithographically defined nanomagnetic structures.

II. ULTRA-HIGH-DENSITY NANOMAGNETIC BAR ARRAYS AND PILLAR ARRAYS

The isolated and interactive nanomagnetic nickel bars were fabricated using electron-beam nanolithography and a lift-off process.[3] All the bars are 35 nm thick. For isolated bars, the bar length was fixed at 1 μm, the spacing between bars was 10 μm, but the bar width varied from 15 to 200 nm. Figure 1 shows a scanning electron micrograph of a Ni bar with a 15 nm width and an average edge variation of 4 nm. For interactive bar arrays, the bar width and length were fixed at 100 nm and 1 μm, respectively. The spacing between bars along the long axis was 2 μm, but the spacing between the bars along the short axis varied from 200 to 600 nm. Therefore the interaction between bars is primarily along the short axis, and the bar arrays can be regarded as isolated rows of one-dimensional interactive arrays. This is very different from that in Ref. 1 where the bars were coupled primarily along the long axis. To illustrate the fabrication precision and uniformity, Fig. 2 shows a large array of Ni bars

Fabrication of single-domain magnetic pillar array of 35 nm diameter and 65 Gbits/in.^{2} density

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Ref-4

(Received 20 June 1994; accepted 31 August 1994)

Using electron beam nanolithography and electroplating, arrays of Ni pillars on silicon have been fabricated. The effects of plating current and feature size on the plating rate were investigated. The pillar arrays have a period of 100 nm and the pillar diameters are uniform and as small as 35 nm. Because of their nanoscale size, shape anisotropy, and separation from each other, each Ni pillar is single domain with only two quantized perpendicular magnetization states: up and down. If each pillar were to represent one bit of information, the density of the pillar arrays would be 65 Gbits/in.^{2}—over two orders of magnitude greater than the state-of-the-art magnetic storage density. The ultrahigh density, together with the single-domain formation, make these pillar arrays very attractive for high-density magnetic storage devices and fundamental magnetics studies.

I. INTRODUCTION

To explore new high-density magnetic storage media and improve our understanding of magnetics, new fabrication techniques for producing closely packed nanoscale magnetic structures are required. The highest packing density is achieved when the magnetic structures are oriented perpendicular to the substrate and thus form a perpendicular magnetic recording media. Previously, several perpendicular recording media were developed and investigated. These include Co–Cr thin films with vertical grains,[1,2] barium ferrite powder with a perpendicular z axis,[3] and vertical ferromagnetic pillars plated through porous Al films[4] or plastics films with nuclear radiated tracks.[5] In all these media, the diameter and magnetization direction of the magnetic grains have a broad continuous distribution; the spacing between the grains varies and is uncontrollable; and each bit is stored over at least several magnetic grains.

In this article, we report the development of a process for fabricating ultrahigh-density arrays of single-domain magnetic pillars for perpendicular magnetic recording media using electron beam nanolithography and electroplating of nickel, a ferromagnetic material. Due to its nanoscale size and shape anisotropy, each pillar is a single domain with magnetization perpendicular to the substrate. We will discuss the factors that are important to the plating of nanoscale pillars such as plating current and feature size.

II. FABRICATION OF MAGNETIC PILLAR ARRAYS

Our fabrication process involves electron beam lithography and electroplating. The reason for using plating is that the popular lift off process cannot be used for high aspect ratio vertical structures. In the lift off process, gradual accumulation of materials at the orifice of each resist template opening during the deposition will eventually close the opening; as a result, the maximum pillar height is about the size of the template opening and large shape anisotropy is difficult to achieve.

A schematic of the process is shown in Fig. 1. A plating base of 10 nm chrome and 50 nm gold was evaporated on a silicon substrate. A high resolution electron beam resist, polymethyl methacrylate (PMMA), of 950 K molecular weight was then spun onto the substrate. The thickness of the PMMA was either 130 or 720 nm depending upon the desired pillar height. Dot arrays with diameters from 35 to 75 nm and spacings from 50 to 1000 nm were exposed in the PMMA using a high resolution electron beam lithography system that has a beam diameter of 4 nm and an accelerating voltage of 35 kV. The electron beam lithography system is a converted scanning electron microscope (SEM) and has been reported elsewhere.[6] The exposed PMMA was then developed in a cellosolve and methanol solution creating a template for the electroplating process.

The nickel plating process used a nickel sulfamate type plating bath. Such type of plating bath is known to produce films with low internal stress as compared to other types of nickel plating baths such as Watts, all chloride, or sulfate.[7] Low stress deposits are required to fabricate ultrahigh-density arrays of nanomagnetic pillars that have high aspect ratios. The nickel sulfamate plating bath consists of 367 g/ℓ nickel sulfamate [$Ni(SO_3NH_2)_2 \cdot 2H_2O$] and 30 g/ℓ boric acid in water yielding a pH of 4. The bath was heated to 50 °C and mechanically agitated at a stirring speed of 100 rpm. The optimum stirring speed for micron scale features was found to be between 100 and 125 rpm. Stirring speeds lower than this resulted in only shallow filling of the template features and speeds higher than this resulted in rough film surfaces. During the plating, the plating current was kept constant by using a current source. The stress in the deposited nickel was tested by plating 0.5 μm thick nickel squares with an area of 25 μm^2. No cracking of the film was observed, except slight bowing at the edges, indicating that the stress was low. After electroplating, the PMMA template was removed in an oxygen ashing process leaving the nanomagnetic pillar arrays.

The nickel plating rate was found to be related to the plating current, the feature size, and the total plating area. The effect of plating current on the plating rate of nanoscale pillars with 720 nm PMMA is shown in Fig. 2. As expected, the plating rate generally increases linearly with plating current. However, at low plating current the plating rate is not a linear function of the current.

The nickel plating rate also depends upon the size of the

Spin-Valve Effects in Transport Perpendicular to Nickel/Silicon/Nickel Diodes

Ref - 5

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Abstract—**We report on fabrication and characterization of a Ni/Si/Ni planar spin-valve device with nanoscale interdigited Ni fingers forming Schottky contact with Si. A large length-to-width ratio of the fingers results in a single domain magnetization which determines a sharp magnetoresistance (MR) response. The magnetization switching field of the fingers is determined by the finger width and finger spacing since the magneto-static interaction between neighboring fingers affects the switching behavior. MR measurements reveal spin-valve effects in the Ni/Si/Ni structure with a MR change of 0.6 % at room temperature. The effects are discussed within a spin-valve model.**

Spin-valve effects in the tunneling perpendicular to ferromagnetic/dielectric/ferromagnetic trilayers have been observed by several groups [1-3]. The magnetoresistance (MR) when the spins of the two ferromagnetic layers are parallel is smaller than that when the spins are anti-parallel. The difference in MR is attributed to the spin-polarized electron tunneling which is dominant at low temperatures. MR changes of 2.5~7.7 % were found at 4.2 K in $Fe/GdO_x/Fe$ structures [2]. As for the spin-vale effect at room temperature, however, an only report was about $Ni/Al_2O_3/Co$ structures which showed a MR change of as small as 0.07 % at room temperature [3]. In this paper, we present a new kind of spin-valve device, ferromagnetic/ semiconductor/ferromagnetic (FM/S/FM) planar structure [4]. For the first time, we report fabrication of a spin-valve structure featuring nanoscale ferromagnetic fingers and observation of spin-valve effects with a MR change of 0.6 % at room temperature.

Since the planar technique on Si has well been established, we propose fabrication of a planar FM/S/FM structure, schemed in Fig. 1, for future magnetic device application. It consists of two sets of interdigited nanofingers on top of a silicon substrate. Each set has 10~20 fingers depending on the finger spacing (Fig.1 shows two of neighboring fingers) and all fingers are 35-nm thick and 14 μm long. But the two sets of fingers have different finger width from each other and therefore different switching field [5].

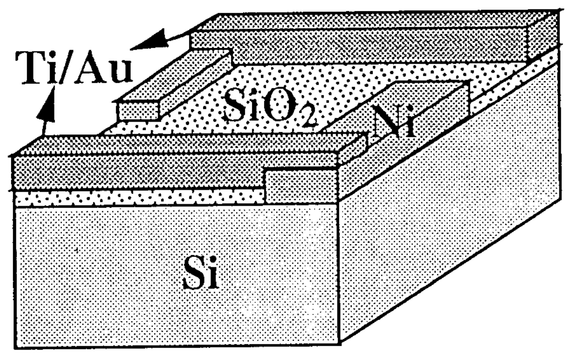

Fig. 1. Schematic structure of a Ni/Si/Ni junction. The Ni finger thickness is 35 nm and the finger length is 14 μm.

The fingers were fabricated in a process as following: An electron beam resist, polymethylmethacrylate (PMMA), was spun onto Si substrate (a 10-nm-thick SiO_2 top layer had been grown by thermal oxidation). Finger patters were exposed in the PMMA using a high resolution electron beam lithography system. The exposed PMMA was then developed in a methanol solution creating a template for HF etching. The etching removed the exposed SiO_2 layer creating a template for electroplating; The ferromagnetic metal plating was made by e-beam evaporation. Finally, the PMMA template was removed by lift-off technique leaving the ferro-magnetic metal fingers. In this work, Ni was used as the ferromagnetic finger to form Schottky barrier with n-type Si of 4-7 Ωcm resistivity. Ohmic contact to the Ni fingers was formed by a Ti/Au film deposited on the top of the fingers.

A typical *I-V* characteristic of the Ni/Si/Ni junction is shown in Fig. 2. The junction is actually a photodetector with Schottky barriers formed by Ni/Si contact. One of the two Schottky diodes

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Effects of sample size and field orientation on pseudo-Hall voltage in micronscale nickel thin-film squares

Ref-6

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Pseudo-Hall effect (PHE) in Ni thin-film squares of 1–5 μm size is measured with a constant current through two leads along one diagonal of the square and the voltage output from leads along the other diagonal. The PHE voltage in response to an in-plane magnetic field depends on the square size and field orientation. The minimum PHE voltage at low field is close to zero only with the 2 μm square containing four symmetrical closure domains leading to a 600% relative change in PHE voltage. The PHE signal is found the largest when the field direction is along the square side while the smallest when along the square diagonal. © *1997 American Institute of Physics.* [S0021-8979(97)63408-8]

Size effects in micronscale magnetoresistive (MR) elements are important for both basic understanding of micromagnetics and high-density magnetic storage technology. Previous studies have observed size effects on the magnetization behavior of micronscale thin-film MR elements. For example, the domain structure of 1–5 μm Ni squares of 35 nm thickness has been characterized by magnetic force microscopy (MFM)[1] showing that the magnetization changes from a single domain at 1 μm width (with the magnetization direction along a diagonal of the square) to a symmetrical multi-domain at 2 μm (with four closure domains) and then to chaos multi-domain at 4 μm or larger. It is then interesting to study how the MR behavior of the micronscale Ni squares may depend on the size. In this article, we report on the pseudo-Hall effect (PHE)[2] in micronscale Ni squares. The PHE is due to the well-known anisotropic MR effect where the electrical field and the current are in different directions. It is useful for reducing thermal drift of MR sensor output.[3] We observe the PHE voltage as a function of the square size and the field orientation with respect to the sample. Our experimental results reveal that a well-defined domain structure may give an excellent MR behavior.

Micronscale Ni thin-film squares with one lead at each corner were fabricated using e-beam lithography and a lift-off technique.[4] In the fabrication, a polymethylmethacrylate (PMMA) resist was first spun onto a SiO_2 substrate. Patterns of squares were exposed in the PMMA using a high resolution e-beam lithography system. The exposed PMMA was removed during development to form a resist template on the substrate. A Ni film of 35 nm thickness was evaporated onto the entire sample using electron evaporator. Finally, the resist was dissolved in acetone, lifting off the Ni film on top of the resist. The Ni squares have side width varying from 1 to 5 μm. Current and voltage leads are arranged on the corner of the square as shown in Fig. 1.

Pseudo-Hall measurements were performed as follows: A constant current (I) is driven across one diagonal direction in the square and the voltage drop (V) across the other diagonal direction is measured as a function of an in-plane magnetic field. We use V/I as the PHE signal since V is actually proportional to I. Figures 2(a), 2(b), and 2(c) show the room temperature PHE response curves of Ni squares of side width at 1, 2, and 4 μm, in sequence, with the field direction along the square side.

The PHE response curve shows a minimum at low field. The minimum value depends on the square size as shown in Fig. 3. The 2 μm square gives the minimum closer to zero than other squares, therefore a larger relative change in the PHE voltage (over 600% for the 2 μm square). The absolute value of the PHE output change is about 50 mV/A when the field direction is along the square side.

Hysteresis effect in the PHE response is indicated by the arrows in Fig. 2. The PHE minimum occurs after the field reverses in direction and the corresponding field position is around 70, 40, and 20 Oe for the square side width of 1, 2, and 4 μm, in sequence, as the field direction is along the square side. We attribute the minimum occurrence to the magnetization reversal in the square. Thus the results show

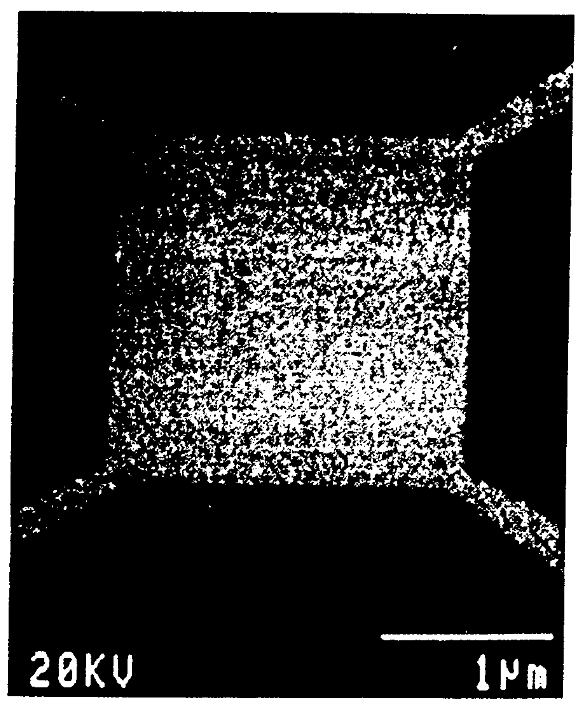

FIG. 1. A SEM picture of the 2 μm Ni square sample.