Spin-Valve Effects in Nickel/Silicon/Nickel Junctions

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***Abstract*– We report on fabrication and characterization of a planar spin-valve device which has two sets of interdigited nanoscale Ni fingers as two electrodes in Schottky contact with Si. The finger width is 75 nm for one set and 150 nm for the other. A large length-to-width ratio of the fingers results in a single domain magnetization and a sharp magneto-resistance (MR) response. The switching field of the finger is determined by the finger width and spacing due to magnetostatic interaction. MR measurements reveal spin-valve effects in the Ni/Si/Ni junctions with MR changes of 0.3~0.6 % at room temperature. The effects are discussed within a spin-valve model.**

I. INTRODUCTION

Spin-valve effects in the tunneling perpendicular to a ferromagnetic/dielectric/ferromagnetic trilayer structure have been observed by several groups [1-5]. 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. In this paper, we present a new kind of spin-valve device, a planar ferromagnetic/ semiconductor/ferromagnetic (FM/S/FM) junction, in which the major conduction mechanism is not tunneling but thermionic emission across the Schottky barrier at the FM/S interface. For the first time, Ni/Si/Ni junctions with nanoscale Ni electrodes are fabricated using electron-beam lithography and characterized by MR measurements.

The FM/S/FM junction was first proposed for magnetic device application by one of the authors [6]. The device structure is illustrated in Fig. 1 with Ni as the FM electrode and Si as the semiconductor substrate. It consists of two sets of interdigited ferromagnetic nanofingers on top of the semiconductor substrate. Each set as an electrode has 10 ~20 fingers depending on the finger spacing (Fig. 1 shows only one finger from each set). The two sets of fingers have different widths and therefore different switching fields as found previously in [7].

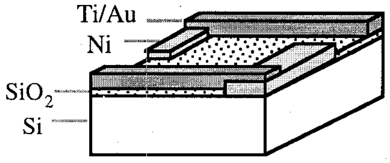

Fig. 1. Schematic structure of a Ni/Si/Ni spin-valve device. The two Ni finger electrodes have different widths.

II. FABRICATION

In the sample fabrication, a polymethylmethacrylate (PMMA) resist was first spun onto Si substrate (a 10-nm-thick SiO_2 top layer had been grown by thermal oxidation). Nanoscale finger patterns 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. A thin Ni film was then deposited onto the entire sample by e-beam evaporation. Finally, the PMMA template was removed by a lift-off technique leaving Ni fingers on the Si substrate. In this work, *n*-type Si of 4-7 Ωcm resistivity was used as substrate. The Ni finger has 35-nm thickness, 14-μm length, 75-nm width for one set and 150-nm for the other. Ohmic contacts to the Ni fingers were formed by a Ti/Au film deposited on the top of the fingers.

III. RESULTS

The *I-V* characteristics of a Ni/Si/Ni junction are shown in Fig. 2. The junction is actually a photodetector with two Schottky diodes formed by Ni/Si contact. One of the two Schottky diodes must be reverse biased whatever bias is applied to the junction. In the thermionic-emission theory, the Schottky reverse-saturation current density is given by $j_{st}= A^* T^2 \exp(-q\phi_b/kT)$ where $q\phi_b$ is the Schottky

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barrier height and A* is the Richardson constant. From the *I-V* data we estimate the Ni/*n*-Si Schottky barrier height to be 0.59 eV.

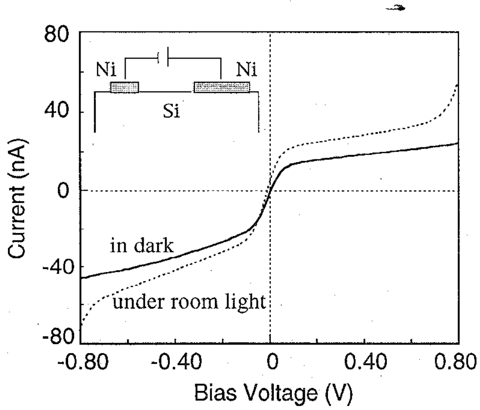

Fig. 2. I-V characteristics of a Ni/Si/Ni junction with Ni finger electrode spacing of 500 nm.

MR measurements were made in dark at room temperature. A 40-mV AC signal was applied to the Ni/Si/Ni junction and its differential resistance was measured using a lock-in amplifier. In the junction with a finger spacing of 500 nm, the differential resistance was found about 10 MΩ. The resistance change, [R(H)–R(0)]/R(0), as a function of magnetic field is shown in Figs. 3 and 4 for the field direction being parallel and perpendicular to the length of fingers, respectively.

As seen in Fig. 3, for a field intensity greater than 400 Oe, the MR response is flat or saturated. In a forward scan of magnetic field starting from the saturation, the resistance undergoes a sharp increase around -50 Oe as shown in Fig. 3(a) for a finger spacing of 500 nm, stays flat and then undergoes a sharp decrease around 380 Oe. Similar effects were observed in samples of a finger spacing of 300 nm, as shown in Fig. 3(b), but the resistance jump occurs at ~290 Oe, much higher than 50 Oe for the 500-nm spacing. The amplitude of MR change was typically 0.3~0.6 % at room temperature (depending on the field orientation and finger spacing) but increased with lowering temperature.

In order to confirm that the observed MR effects originate in the ferromagnetic fingers, we have tested devices with non-ferromagnetic (e.g. Ti/Au) fingers. No MR effect was found in these samples. In fact, the hysteresis behavior in the MR response as shown in Figs. 3 and 4 also confirms the ferromagnetic origin of the MR effects.

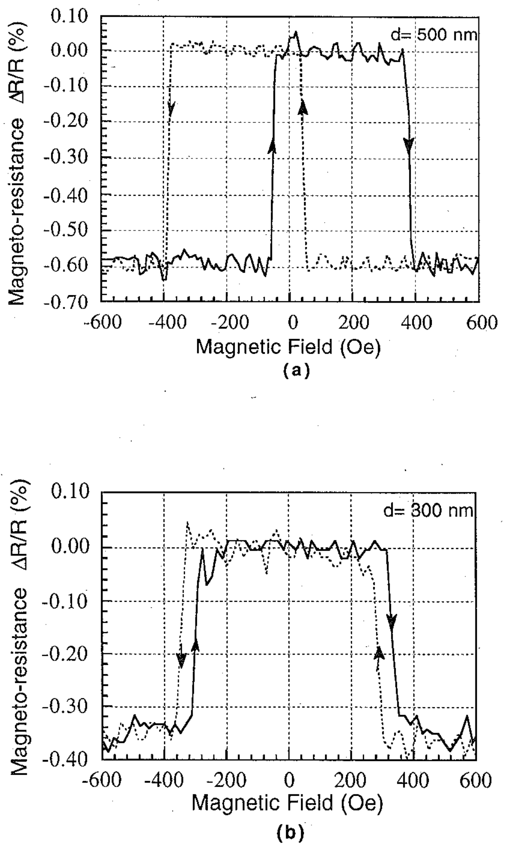

Fig. 3. Magnetoresistance as a function of magnetic field and scan direction of the field as indicated by arrows. The field is parallel to the length of fingers. (a) For a finger spacing of 500 nm; (b) For a finger spacing of 300 nm. T= 300 K.

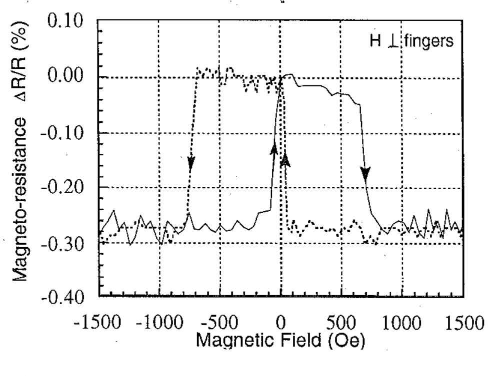

Fig. 4. Magnetoresistance as a function of magnetic field and scan direction of the field as indicated by arrows. The field direction is perpendicular to the finger length. The finger spacing is 500 nm.

IV. DISCUSSION

The observed effects can be explained using a spin-valve model: the resistance of the junction depends on the relative spin orientation of the two FM finger sets. Since the two finger sets have different switching fields, at certain magnetic field range, the two sets of fingers have anti-parallel spin orientation, 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. Since the junction resistance is much larger than the Ni film resistance, the MR effect in the Ni film can be neglected.

The abrupt change in resistance indicates well-defined switching fields of the Ni fingers. A single domain magnetization of the fingers can explain the well-defined switching fields. As has been studied by using magnetic force microscopy [8] that, when a finger length-to-width ratio is sufficient high, the finger presents a single domain with the magnetization direction parallel to the finger length.

The switching field of 50 Oe observed for the finger spacing of 500 nm differs significantly from that of 290 Oe for the finger spacing of 300 nm. This implies that magnetostatic interaction between the fingers play an important role in the switching behavior. From a magnetic dipole model, we can estimate the mean field of a Ni finger on its neighbor finger as $2p\ (1/d\ - 1/\sqrt{d^2 + l^2})\ /\ l$ where p is the dipole strength, d, the finger spacing, and l, the finger length. The calculated mean field is of order of 1 Oe for d= 500 nm but it should be noted that the magnetic field produced by a finger on its neighbor is not uniform and the magnetization reversal in the finger is predominately affected by the external field at the end of the finger.

It remains unclear why the Ni/Si/Ni junction resistance is higher with an anti-parallel spin orientation of neighboring fingers than that with a parallel one. The finger spacing of 300 and 500 nm may rule out the possibility of spin-polarized tunneling in the Ni/Si/Ni junction. It is actually the thermionic emission of electrons over the Schottky barrier to govern the conduction of the junction. One explanation for the spin-valve effects is the spin-dependent scattering at the Ni/Si interface since the electron spin-coherent length in Si is larger than 0.5 μm. Further evidence is needed to establish a model for the spin-valve effects.

V. SUMMARY

We have observed spin-valve effects in the Ni/Si/Ni junctions with two nanoscale Ni finger electrodes of different widths and then different switching fields. An anti-parallel spin orientation of neighbor fingers results in a larger resistance of the junction than a parallel spin orientation. The magnetoresistance response of the junctions with varying Ni finger spacing and magnetic field orientation has been measured. The mechanism of the spin-valve effects is different from the well-known spin-polarized tunneling. Further study is underway to determine the spin-dependent scattering effect at the Ni/Si interface.

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