# Integration of Bimetallic Co–Ni Thick Film-Based Devices for Spintronics

Trupti Mohota and Kailash Nemade

***Abstract*— Spintronics is the exploitation of both the degree of freedom of electron that is spin as well as the charge, which leads to tremendous development in the field of microelectronic applications. In this paper, bimetallic Co-Ni-based spin FET device is fabricated, and its magnetoresistance behavior has been studied. While, spin current as a function of thickness of Co–Ni-based concatenable spin switch has been studied. The results obtained for spin current using simulation and experimentation show good agreement.**

***Index Terms*— Bimetallic, Co–Ni thick film, spintronics.**

## I. INTRODUCTION

THE devices with enhanced functionality have great attention for the next generation microelectronics. In this context, the rising branch of electronics that is spintronics has capabilities to satisfy requirements of the next generation microelectronics. The spintronic devices exhibit interesting features like high speed, lower power consumption, and higher integration density [1]–[3].

Marti *et al.* [4] in his results showed that the antiferromagnet-based devices are the key active element in spintronics. These devices have capability of reading, writing, and storing information. Mohamed *et al.* [5] fabricated the carbon nanotube spin FET (s-FET) device, which has magnetoresistance (1.8%) at the low temperatures due to spin-dependent transport. Datta *et al.* [6] designed the giant spin-Hall effect-based Read and Write units that can be integrated into a single spin switch with input–output isolation. In his work, spin switches are interconnected without any external amplification to work as logic operations. Such types of devices are also used in non-Boolean logic [6]. Bea *et al.* [7] report the properties of $BiFeO_3$-based spintronic devices, with novel functionalities to a number of technological fields. The spin-valve structure of $BiFeO_3$ heterostructure has magnetic configuration, which is switchable by an electric field, via the existence magnetoelectric coupling [7]. The integration of spin-based memory and logic circuits based on a hybrid graphene/ferromagnet material system is reported by Dery *et al.* [8]. The designed circuit has high-speed, small-area, and low-power consumption [8]. Meng *et al.* [9] fabricated the full adder, which determines the speed and chip density of a processor. The magnetic processor (sprintronics) when compared with traditional microprocessor is much faster and has potential features of nonvolatile, lower power consumption, and higher integration density [9].

Inspiring from the above discussion, in this paper, we planned to investigate the performance of Co–Ni-based s-FET. Similarly, we studied the spin current parameter for concatenable spin switch.

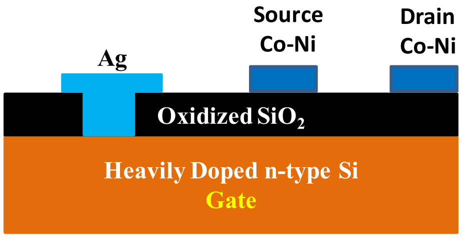

Fig. 1. Schematic drawing of an s-FET structure showing Co–Ni on oxidized $SiO_2$ and heavily doped n-type Si.

## II. EXPERIMENTATION

The back gate-based configuration was preferred for fabrication of s-FET. In the fabrication of s-FET, bimetallic Co–Ni is used as ferromagnetic electrodes, as shown in Fig. 1. The thermally oxidized $SiO_2$ layer was used as a gate insulator, whereas heavily doped n-type silicon film as a gate electrode. On the insulating $SiO_2$ substrate, the source and drain electrodes were deposited using optical lithography. Two different s-FETs were fabricated with a channel length and width of: 1) 7 $\mu$m × 500 $\mu$m and 2) 7 $\mu$m × 250 $\mu$m. The electron beam evaporation system was used to deposit Co–Ni of thickness 135 nm. The passage between both electrodes was polished by a few layers of graphene. To measure magnetoresistance, the devices were kept in cryostat. The cryostat was kept in an electromagnet system. The parallel magnetic field is applied to the plane of the substrate. The measurements were carried out at room temperature (303 K) and at 5 K. The magnetic field was varied from 0 to 2000 Oe, back to −2000 Oe, and stopped at 2000 Oe. The magnetoresistance characteristic was determined for one of the electrodes. The spin-resolved total density of states (DOS) in a bimetallic Co–Ni film was studied and discussed by means of Monte Carlo simulations.

The precision in the operation of device is confirmed by recording the magnetic properties [using superconducting

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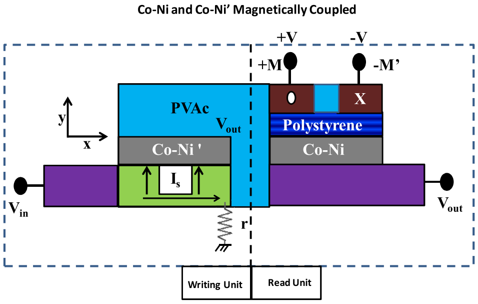

Fig. 2. Schematic spin switch showing the Write and Read units.

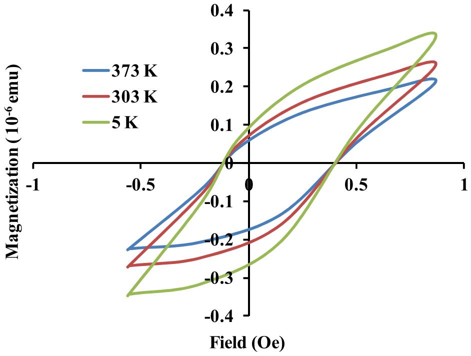

Fig. 3. Magnetic properties of the bimetallic Co–Ni s-FET at different temperature.

quantum interference device (SQUID)] and giant magnetoresistance (using cryostat) several times. No significant deviation is observed in the performance of the device.

The concatenable spin switch based on bimetal Co–Ni was designed, which consists of Write and Read units, as shown in Fig. 2. In this scheme, Writing and Reading units are electrically inaccessible, but magnetically coupled. In a concatenable spin switch, the output of one unit can drive the input of the next unit.

## III. RESULTS AND DISCUSSION

The magnetic properties of a bimetallic Co–Ni-based device were measured by a SQUID are shown in Fig. 3. The magnetic properties of the device is studied at 5, 303, and 373 K. The typical magnetic behavior was observed for the device. The coercive force of the order of ~135 Oe was obtained from the hysteresis curve for all temperatures. For all the systems, the magnetic properties remain unchanged. This can be mainly due to no structural change in a bimetallic Co–Ni layer. Another reason is that during the annealing of Ni in the presence of Co, its magnetic properties remain unchanged.

Fig. 4(a) shows the resistance dependence of the device for a channel width of 500 $\mu$m at 303 K. The plot clearly shows that there is no significant variation in the resistance value as a function of magnetic field. Fig. 4(b) shows the variation of resistance with field for a device having a channel width of 500 $\mu$m at 5 K. The minute observation of Fig. 4(b) shows resistance peaks nearly at 0 Oe and varies with direction of the sweep. Fig. 5(a) and (b) shows the identical behavior as discussed for a device having a channel width of 500 $\mu$m at 303 and 5 K. A noticeable giant magnetoresistance peaks are observed for both devices

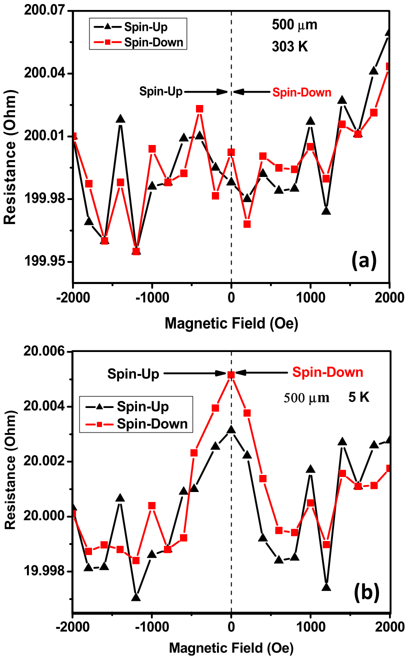

Fig. 4. Magnetoresistance for s-FET with $W = 500$ $\mu$m at (a) 300 and (b) 5 K.

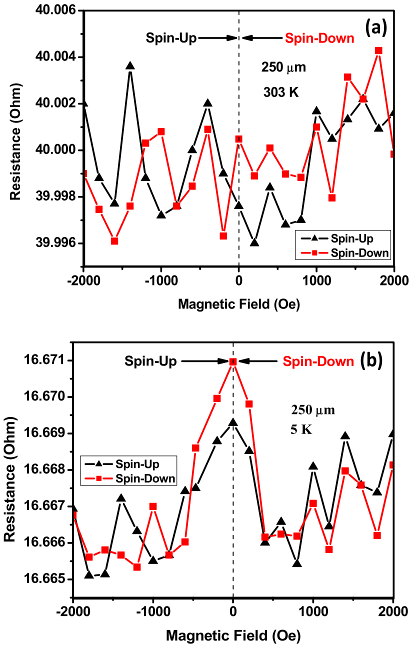

Fig. 5. Magnetoresistance for s-FET with $W = 250$ $\mu$m at (a) 300 and (b) 5 K.

at temperature 5 K [10]. The two different values of resistance were resulted by applying a large positive or negative voltage through the barrier to switch. This shows the capability of device to use it as a spin valve. A detailed analysis of the spin valve application and mechanism of these devices is to be planned in the near future [11].

In general, in metal at room temperature, giant magnetoresistance effect is very small. But still it found a substantial importance in technology for magnetic disks and as the sensors of magnetic fields. The performance of device presented in Figs. 4 and 5 may improve by producing fine layers of

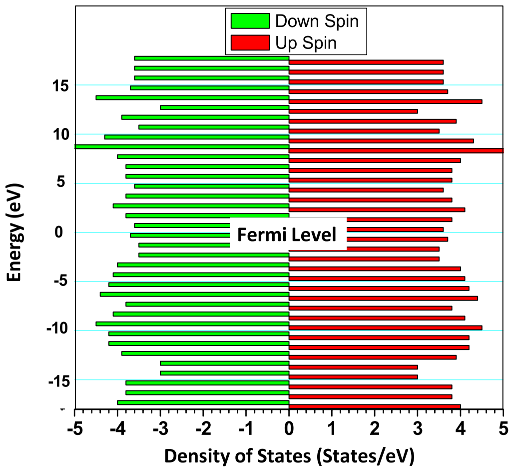

Fig. 6. Total DOS for bimetallic Co–Ni in s-FET.

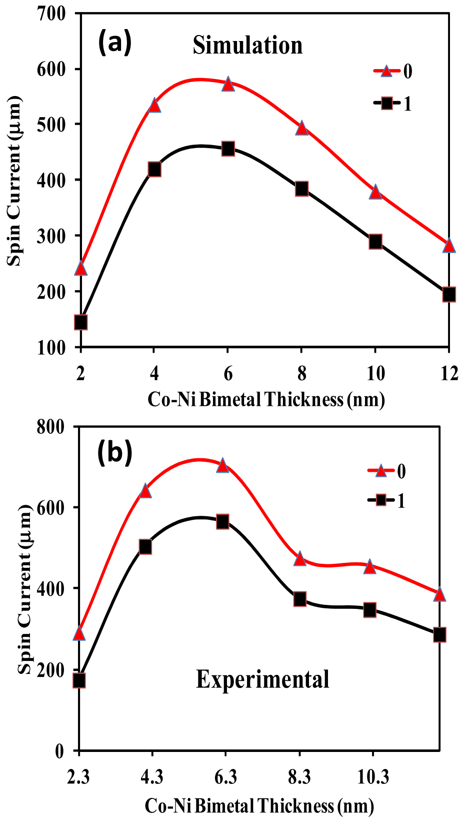

Fig. 7. Spin current during write "0" and "1". (a) Simulation. (b) Experiment.

bimetals on the nanometer scale. Yuasa *et al.* [12] reported the giant magnetoresistance in single-crystal Fe/MgO/Fe at room temperature. The result of this paper shows that magnetoresistance ratio of the order of 180% at room temperature is observed. This much higher value of giant magnetoresistance is attributed to the coherent spin-polarized tunneling due to symmetry of electron wave functions [12].

Fig. 6 shows the plot of spin-resolved total DOS for bimetallic Co–Ni in s-FET. The lowest energy spin state indicates the suitableness of Co–Ni for device fabrication. The spin state for both electronic spin is attributed to the antiferromagnetic coupling. From the plot of spin-resolved total density, the majority channel possesses a large bandgap. Due to this, transport is dominated by the minority electrons, and thus current flow in this system is spin polarized.

The charge current ($I_e$) flowing in the spin Hall metal (SHM) is determined from circuit simulation, and the corresponding spin current is shown as follows [13]:

$$I_S = \frac{A_{\text{MJT}}}{A_{\text{SHM}}}\theta_{\text{SHM}}\left(1 - \sec h\left(\frac{t_{\text{SHM}}}{\lambda_{\text{sf}}}\right)\right) I_e \tag{1}$$

where magnetic junction tunnel ($A_{\text{MJT}}$) is the cross-sectional area of the MJT, $A_{\text{SHM}}$ is the cross-sectional area of spin Hall metal, $\theta_{\text{SHM}}$ is the spin Hall angle, and $\lambda_{\text{sf}}$ is the spin flip length ($\lambda_{\text{sf}} = 1.5$ nm). The term in the parenthesis shows the reduction in spin Hall current density as spin Hall metal is compact. The variation of spin current with thickness of Co–Ni bimetal estimated using simulation and experimentation is shown in Fig. 7(a) and (b), respectively. The plot of experimentation nearly matches with the results of simulation. The spin current during "0" writing is higher than "1". Whereas, the optimized value of spin current in both cases observed ∼6-nm thickness of Co–Ni bimetal.

## IV. CONCLUSION

The result of this paper indicates that bimetallic Co–Ni thick film-based devices are suitable for spintronics. SQUID analysis shows that bimetallic Co–Ni has direct dependence on magnetic field. The giant magnetoresistance peaks were observed for both widths (500 and 250 $\mu$m) at 5 K, which is attributed to the spin-dependent transport s-FET devices. In the light of above results and discussion, spin valve is an another strong application of this paper.

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## REFERENCES

[1] Z. H. Xiong, D. Wu, Z. V. Vardeny, and J. Shi, "Giant magnetoresistance in organic spin-valves," *Nature*, vol. 427, pp. 821–824, Feb. 2004.

[2] Y. Ma, Y. Dai, W. Wei, and B. Huang, "Engineering intriguing electronic and magnetic properties in novel one-dimensional staircase-like metallocene wires," *J. Mater. Chem. C*, vol. 1, no. 5, pp. 941–945, 2013.

[3] S. A. Wolf *et al.*, "Spintronics: A spin-based electronics vision for the future," *Science*, vol. 294, no. 5546, pp. 1488–1495, 2001.

[4] X. Martí, I. Fina, and T. Jungwirth, "Prospect for antiferromagnetic spintronics," *IEEE Trans. Magn.*, vol. 51, no. 4, Apr. 2015, Art. no. 2900104.

[5] M. A. Mohamed, N. Inami, E. Shikoh, Y. Yamamoto, H. Hori, and A. Fujiwara, "Fabrication of spintronics device by direct synthesis of single-walled carbon nanotubes from ferromagnetic electrodes," *Sci. Technol. Adv. Mater.*, vol. 9, no. 2, pp. 025019–025024, 2008.

[6] S. Datta, B. Behin-Aein, and S. Salahuddin, "Non-volatile spin switch for Boolean and non-Boolean logic," *Appl. Phys. Lett.*, vol. 101, no. 25, pp. 252411–252421, 2012.

[7] H. Bea *et al.*, "Integration of multiferroic BiFeO$_3$ thin films into heterostructures for spintronics," *IEEE Trans. Magn.*, vol. 44, no. 7, pp. 1941–1945, Jul. 2008.

[8] H. Dery *et al.*, "Nanospintronics based on magnetologic gates," *IEEE Trans. Electron Devices*, vol. 59, no. 1, pp. 259–262, Jan. 2012.

[9] H. Meng, J. Wang, and J.-P. Wang, "A spintronics full adder for magnetic CPU," *IEEE Electron Device Lett.*, vol. 26, no. 6, pp. 360–362, Jun. 2005.

[10] M. N. Baibich *et al.*, "Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices," *Phys. Rev. Lett.*, vol. 61, pp. 2472–2478, Nov. 1988.
[11] M. Jullière, "Tunneling between ferromagnetic films," *Phys. Lett. A*, vol. 54, no. 3, pp. 225–226, Sep. 1975.
[12] S. Yuasa, T. Nagahama, A. Fukushima, Y. Suzuki, and K. Ando, "Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions," *Nature Mater.*, vol. 3, pp. 868–871, Oct. 2004.
[13] L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman, "Spin-torque switching with the giant spin Hall effect of tantalum," *Science*, vol. 336, no. 6081, pp. 555–558, May 2012.

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