ON MAGNETIC NANOPARTICLES DETECTION USING PLANAR HALL EFFECT SENSORS

M. Volmer[1,2], M. Avram[2]
[1]Transilvania University of Brasov, 29 Eroilor, Brasov 500036, Romania
E-mail: volmerm@unitbv.ro
[2]National Institute for Research and Development in Microtechnologies,
Str. Erou Iancu Nicolae 32B, 72996 Bucharest, Romania
E-mail: marioara.avram@imt.ro

Abstract*–In this paper we present aspects concerning magnetic nanoparticles detection using a planar Hall effect magnetometer, disk-shaped of 1mm diameter, build from a single Permalloy layer, 20 nm thick, deposited on oxidized Si substrate. This device allows us to measure the stray magnetic field generated by superparamagnetic beads which are magnetized by an external field. During the experiments we found strong sensor signal dependence, both in shape and magnitude, with the particles at different positions. The results are explained by means of micromagnetic simulations were magnetostatic interactions between magnetic nanobeads and sensor are clearly highlighted.*
Keywords: *Magnetic sensors, Planar Hall Effect, superparamagnetic beads, Micromagnetic simulations, Lab-on-Chip.*

1. INTRODUCTION

The idea of lab-on-a-chip (LOC) device is basically to reduce biological or chemical laboratories to a microscale system, hand-held size or smaller. The recent development of microfluidic systems for lab-on-a-chip applications using magnetic micro/nano bead-based biochemical detection is a promising approach. In these systems the magnetic beads are used to label the biological structures of interest. Depending on their size, we can talk about micro beads (diameters of about 1-3 μm) and nanobeads which can have diameters between 10-200 nm. Because these beads are made, usually from magnetite or maghemite and have so small dimensions, they don't have a net magnetization in the absence of an external magnetic field. This aspect is crucial for LOC application. On the other hand, when a magnetic field is applied these particles acquire a net magnetic moment and they behave like very small magnets. The fields produced by these beads are usually measured, in LOC applications, using giant magnetoresistance (GMR), tunnelling magnetoresistance effect (TMR) or planar Hall effect (PHE) spin-valve sensors [1-3]. The PHE sensors based on the anisotropic magnetoresistance (AMR) effect have become very attractive [2, 3] because of thermal stability and a higher signal-to-noise ratio (S/N) when compared to spin valve GMR sensors [2]. The PHE is related to the rotation process of magnetic domains in the sensing layer and the output voltage is of the type $U_{PHE} \sim I_{sens} \cdot M^2 \cdot \sin 2\theta$, where θ is the angle between magnetisation vector and the sensor driving current, I_{sens}; M is the magnetization of the sensing layer. For this reason the PHE sensors have a noise level (in the $1/f$ dominated low-frequency regime) about 20 times lower than the GMR sensors. A very good linearity and sensitivities between 3 μV/Oe, [2] to 7 μV/Oe, [3] for a driving current of 1 mA trough the sensor, are reported for applied fields in the range of ±15 Oe. A typical PHE sensor used for magnetic bead detection has a generic structure of the type exchange layer/magnetic sense layer/passivation layer [2], which is patterned to a cross-shape or disk-shape device. Some other typical structures used to build PHE sensors are trilayers of the type Co(10 nm)/Cu(2 nm)/NiFe(10 nm) [4] or exchange bias spin valves like Ta(/NiFe(16 nm)/Cu(1.2 nm)/NiFe(2 nm)/IrMn(15 nm)/Ta(5 nm) [5]. In these structures, the exchange biasing field due to AF layer, like FeMn or IrMn, is strong enough to fix the magnetization of the FM pinned layer. When a magnetic field is applied in the film plane, perpendicular to biasing field and driving current, the magnetization of the FM free layer will rotate coherently when sweeping the external magnetic field [3] and a signal, U_{PHE}, is obtained. It has to mention two effects that can lower the sensor's sensitivity: (i) the shunting effect due to nonmagnetic and pinned ferromagnetic layers (i.e., the effective current which is flowing through the sensing layer is smaller than I_{sens}) and (ii) the sensor sensitivity

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dependence with the anisotropy field, H_K, and the exchange field, H_{ex} of the type [5] $S \sim 1/\left(H_K + H_{ex}\right)$. Higher values for H_K and H_{ex} means a more ordered magnetic state but implies a higher torque to rotate the magnetisation of the sensing layer. In this paper we present a PHE sensor, used for magnetic nanobeads detection, made from a single Permalloy ($Ni_{80}Fe_{20}$) layer deposited on oxidised Si substrate.

2. RESULTS AND DISCUSSION

Permalloy based PHE sensors, disk-shaped of 1 mm diameter and 20 nm thick, were deposited on oxidised Si substrate. No magnetic anisotropy axis has been defined during the deposition. On each chip four PHE sensors have been defined, Fig. 1(a). The chip was mounted on a grid which is made from a soft magnetic material; the remnant magnetic induction of the grid is about 2 G. To overcome the absence of the anisotropy and exchange fields, we used a biasing field, H_{bias}, which creates a relatively uniform magnetisation state in the sensing layer, Fig. 1(b). The optimum value is H_{bias}=100 Oe which was found by tests and confirmed by micromagnetic simulations. The structure of the disk-shaped PHE sensor used for micromagnetic simulations and the superparamagnetic (sppm) nanobeads located above the centre of the sensing layer are presented in Fig. 1(c).

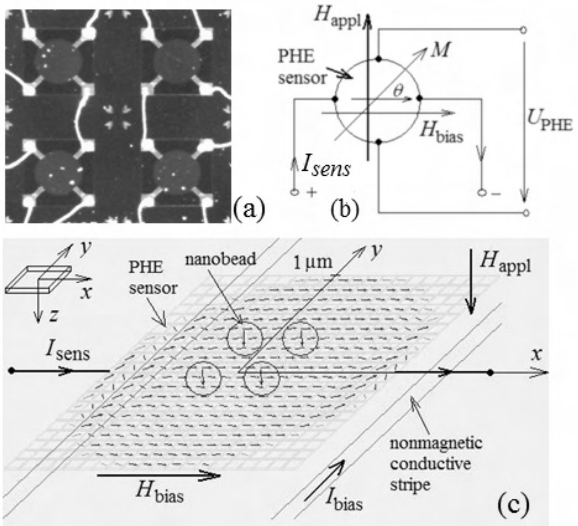

Fig. 1. (a) The PHE sensors, (b) the setup used for biasing the PHE sensor and (c) the structure of the disk-shape spin valve PHE sensor used for micromagnetic simulations and the nanobeads located above the centre of the free layer.

A freeware micromagnetic simulator, SimulMag, was used to design a generic sensor structure, the polarising system, sppm nanobeads, Fig. 1(c), and to analyse the behaviour of this complex system. The PHE structure has a diameter of 2 µm; the sensing layer is divided into a large number of Permalloy single domains 10 nm thick and 95 nm each side. The distance between the adjacent domains is *d*=5 nm which is equivalent with an inter-grain spacing. The cell size used to build the mesh is higher than the exchange length but this is rather a phenomenological model, inspired from the film structure. This approach was used, previously, to describe the magnetization curves, GMR and planar Hall effect in such structures and the agreement with experimental data was very good [6]. The saturation magnetization of the $Ni_{80}Fe_{20}$ layers was set to 800 emu/cm^3. No anisotropy axis was defined in this approach but a biasing field, H_{bias}, generated by the current I_{bias}, was used to define a relative uniform magnetisation state, Fig. 1(c). The conductive stripe (6000 nm long, 2000 nm wide and 200 nm thick) is placed beneath the sensor at a distance of 200 nm. The sppm nanobeads considered for simulations have a diameter of 200 nm and are placed at 200 nm above the sensor's surface. The saturation magnetisation of these nanobeads is M_b=110 emu/cm^3.

Fig. 2 presents the PHE field characteristics measured on one structure from Fig. 1(a), when H_{appl} is in the film plane, like in Fig. 1(b). The measurements are made without and with sppm nanobeads of maghemite (10-12 nm in diameter) on the sensor surface, like we see in the inset.

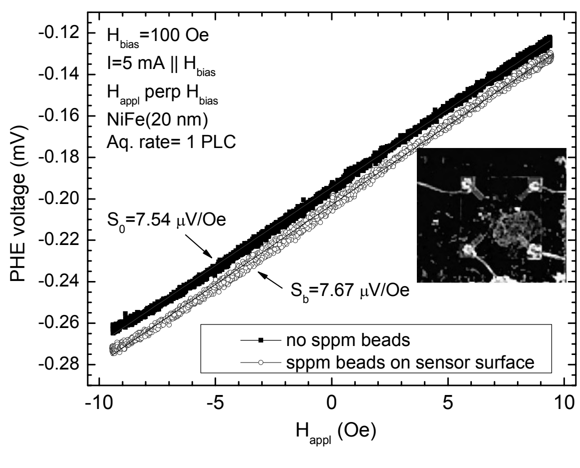

Fig. 2. The field dependences of the PHE signal when H_{appl} is directed in the film plane; the measurements are made without and with sppm nanobeads of maghemite placed over the sensor surface.

We see, from Fig. 2, that field dependences are almost identical in both cases and only a small drift can be observed. For nanobeads detection this behaviour is not useful because cannot offer a net and unambiguous signal. At small applied fields the sppm nanobeads present a very small magnetic moment and their contribution to the total field inside of the sensor is negligible. Basically, these nanobeads have to be magnetised in fields higher than 200 Oe, but for these values the sensor saturates and no signal can be obtained [2, 3]. Fig. 3 illustrates this behaviour, obtained by micromagnetic simulations, when H_{appl} is directed over the y axis like in Fig. 1(b).

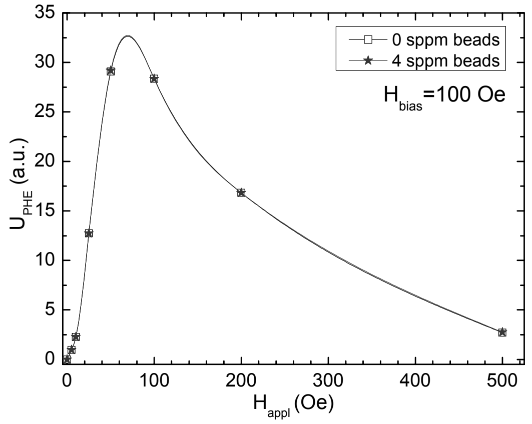

Fig. 3. The micromagnetic simulations of the sensor response, when H_{appl} is directed like in Fig. 1(b), with and without sppm nanobeads on its surface, Fig. 1(c).

To overcome this limitation, we choose to apply the field perpendicular to the sensor surface like in Fig. 1(c). Because the sensor is not sensitive to perpendicular fields, only the in plane components of the field generated by the beads will produce a rotation of the sensing layer magnetisation. Higher values of H_{appl} can be used to magnetise the nanobeads without the risk to saturate the sensor. Because beneath the sensors is a magnetic grid, the field and magnetic moments distributions inside the sensor will be affected by the presence of this material. The typical "S" shape field dependence of the Hall voltage will not be observed, Fig. 4. Instead, what we obtain are typical AMR field dependences measured in a Hall setup. Fig. 4(a) presents the measured signal in the absence and the presence of sppm nanobeads placed on the sensor's surface in a position denoted with "SE". Fig. 4(b) presents micromagnetic simulations of the AMR effect in such structure in the frame of the model presented above, Fig. 1(c).

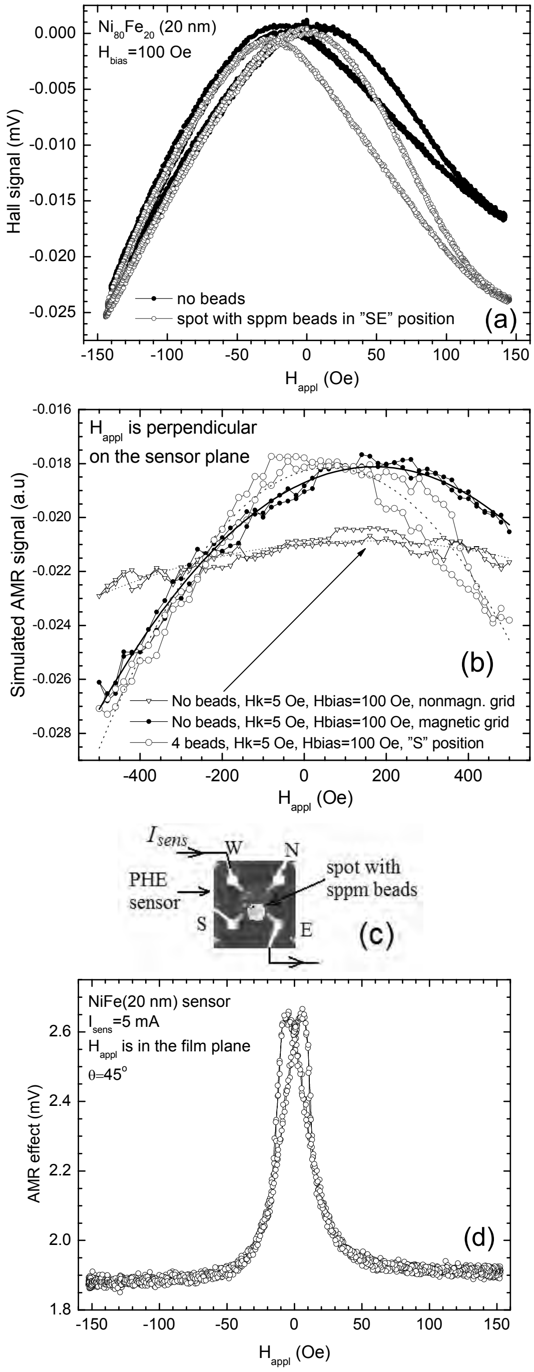

Fig. 4. The output of the PHE sensor (a) measured and (b) simulated considering the setup presented in Fig. 1(c); the beads position on the sensor surface (c) and (d) AMR effect measurement on this sensor without nanobeads; I_{sens}=5 mA.

Fig. 4(c) explains the notations regarding the position of nanobeads on the surface. The beads were placed on the surface using a sharp tip made from wood which has been immersed in aqueous solution that contains the maghemite nanobeads. Because of the surface tension the same quantity of liquid will remain on the tip for each immersion. We had this confirmation in previous experiments by placing drops of ferrofluid on paper and measuring the diameters of the spots. Also, we have used an analytical microbalance to measure the mass of one drop which was found to be about 20 µg. After water evaporation the mass of nanobeads that remains was much smaller than 10 µg and cannot be weighed. From these data and plots, Fig. 4(a), we have an image of the detection sensitivity of this sensor.

Comparing the shapes of the field characteristics presented in Fig. 4(a) and Fig. 4(d) we have the confirmation that the signals represent typical AMR curves. This is due to the magnetic grid which facilitates the appearance of the in plane magnetic fields components. Field components that are parallel or perpendicular on the driving current will not give a signal because $\sin 2\theta \approx 0$. The other components that are close to 45° or 135° give an important signal which corresponds to the AMR effect. The micromagnetic simulations give a good qualitative agreement and show, also, the field behaviour of the AMR effect when the grid is nonmagnetic. As expected, an almost flat characteristic is obtained because the sensor is not sensitive for perpendicular applied magnetic fields. We performed micromagnetic simulations and we found that the signal depends on the nanobeads positions over the sensor surface. Our experiments confirm these results. Fig. 5 presents field dependence of the signal when the beads are placed in the ”N” position above the sensitive layer.

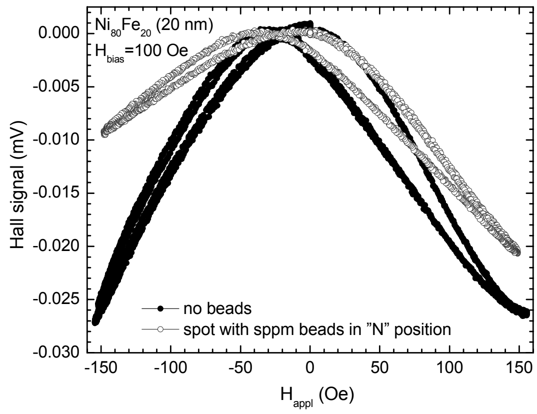

Fig. 5. The Hall signal measured for sppm nanobeads placed in ”N” position above the sensitive layer; I_{sens}=5 mA.

From Fig. 4(a) and Fig. 5 we see a dependence of the signal output on the nanobeads position over the sensor surface. It is to mention that before each new measurement the surface was washed in order to remove the sppm nanobeads and a strong biasing field, higher than 100 Oe, was applied in order to re-set a uniform magnetic state in the sensing layer.

3. CONCLUSIONS

In this paper we have presented aspects regarding maghemite nanobeads detection using a PHE sensor made from a single layer of Permalloy, 1 mm in diameter and 20 nm thick. We found good sensitivity detection and a position dependence of the signal both in amplitude and shape. The experimental data was interpreted by means of micromagnetic simulations. The influence of the magnetic grid on the sensor behaviour has been highlighted. To improve the detection limit, micrometer sized spintronic PHE sensors will be used.

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