

# Size dependent magnetoresistive characteristics of PSV structures for magnetic field sensing applications

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Pseudo spin valves (PSV) having the multilayer structure of Ta (20 nm) / CoFe (10 nm) / Cu (3 nm) / CoFe (1 nm) / NiFe (15 nm) / Ta (10 nm) were microfabricated in order to be used in magnetic field sensing application. The PSV structures were patterned into rectangular stripes having 1000  $\mu\text{m}$  in length and the width ranging from 0.5  $\mu\text{m}$  to 200  $\mu\text{m}$ . The influence of the pseudo spin valve stripe width on the switching fields, the magnetoresistive ratio and on the magnetic field sensitivity has been studied. In addition, the effect of the applied magnetic field direction relative to the PSV stripe long axis has been discussed. It was shown that both the stripe width and the applied field direction are strongly affecting the magnetoresistive characteristics.

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## 1. Introduction

Sensing systems developed for the detection of magnetic fields have always been an essential component within numerous devices and applications, the most relevant including the automotive and biomedical ones. A broad range of magnetic field sensing techniques were developed in the course of time, from fluxgate, Hall or SQUID sensors to magnetoresistive sensing devices (AMR, GMR and TMR) [1]. Giant magnetoresistive (GMR) sensors are widely used nowadays in magnetic field sensing applications due to their relative small size, low cost and high sensitivity [2], [3]. A typical GMR structure consists of two ferromagnetic thin film layers separated by a non-magnetic conducting layer. In these multilayer structures, the electrical resistance depends on the relative orientation of the magnetization in the two ferromagnetic layers, the resistance of the multilayer structure is higher in the antiparallel configuration and lower in the parallel configuration. One frequently used type of multilayer structures that exhibit the giant magnetoresistance effect (GMR) is represented by pseudo spin valves. In such structures, in order to observe the GMR effect, it is mandatory to use ferromagnetic layers with different coercive fields [4]. As a consequence, there is a field range in which the magnetic moments of the soft and hard magnetic layers are antiparallel and the electrical resistance of the multilayer structure reaches the maximum value. The switching fields of the soft and hard ferromagnetic layers must be carefully tailored in order to provide a linear response which is required for magnetic field sensing application, in contrast to MRAM applications that require well defined magnetic states and a sharp magnetization switching.

Magnetization reversal in micron or submicron patterned ferromagnetic thin films and in coupled multilayer structures was intensively studied for MRAM applications [5], [6]. It was shown that the magnetization switching it is strongly dependent on the patterned element size and its aspect ratio [7], [8]. In this paper, with the aim of using PSV magnetoresistive structures as magnetic field sensors, we studied the influence of the PSV stripe width on the magnetoresistive ratio and on the magnetic field sensitivity. The magnetoresistive response of PSV stripes with various widths has been investigated in order to determine the optimum lateral dimensions for which the maximum magnetic field sensitivity is obtained. It is shown that the magnetoresistive characteristics can be significantly enhanced by tuning the width of the PSV stripes. Also, the influence of the applied field direction relative to the PSV stripe long axis it is discussed.

## 2. Experimental details

Pseudo spin valve structures with the multilayer structure of Ta (20 nm) / CoFe (10 nm) / Cu (3 nm) / CoFe (1 nm) / NiFe (15 nm) / Ta (10 nm) were deposited on Si/SiO<sub>2</sub> substrates, using a high vacuum rf/dc magnetron sputtering system. The ferromagnetic layers were deposited from sputtering targets with composition of Co<sub>50</sub>Fe<sub>50</sub> and Ni<sub>81</sub>Fe<sub>19</sub> (targets composition are given in at. %). For the hard ferromagnetic layer a CoFe layer was used while for the soft ferromagnetic layer, a CoFe / NiFe composite layer was used in order to benefit from the low coercive field of the NiFe layer and the relatively high MR ratio given by the CoFe.

By using e-beam lithography and lift-off techniques, the PSV samples were patterned into rectangular stripes

having  $1000\ \mu\text{m}$  in length and the width ranging from  $0.5\ \mu\text{m}$  to  $200\ \mu\text{m}$ . Contact leads were defined at the ends of each magnetoresistive stripe, as can be seen from Fig. 1. The contact leads were defined by direct write laser lithography, followed by  $150\ \text{nm}$  thick gold layer deposition and lift-off.

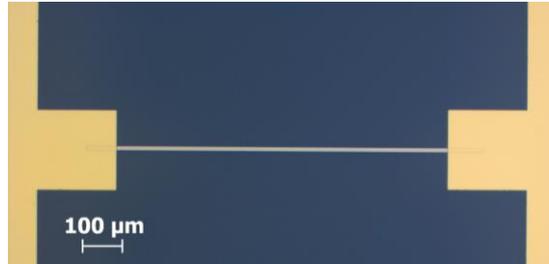


Fig. 1. Optical microscope photograph of a  $1000\ \mu\text{m} \times 5\ \mu\text{m}$  magnetoresistive stripe having two contact leads deposited at the stripe ends

The magnetoresistance curves were obtained by measuring the electrical resistance change under an external magnetic field. For the magnetoresistance measurements a bias current of  $1\ \text{mA}$  was used. During the measurements, the magnetic field was applied in the plane of the multilayer structure, in two different configurations relative to the PSV stripe long axis: longitudinal and transverse. In the longitudinal configuration, the magnetic field was applied parallel with the PSV long axis and in the transverse configuration the magnetic field was applied perpendicular to the PSV long axis.

### 3. Results and discussion

The magnetoresistive ratio dependence on the pseudo spin valve stripe width for the longitudinal configuration is presented in Fig. 2(a) and the normalized magnetoresistance curves for stripes having the width of  $0.5\ \mu\text{m}$ ,  $1\ \mu\text{m}$ ,  $2.5\ \mu\text{m}$  and  $40\ \mu\text{m}$  are shown in the inset of Fig. 2(a). We can observe that the magnetoresistive ratio is increasing as the width of PSV stripe decreases. For a  $200\ \mu\text{m}$  wide stripe the MR ratio is  $4.77\ \%$  and by decreasing the width to  $0.5\ \mu\text{m}$ , the magnetoresistive ratio is increasing to  $5.84\ \%$ . The enhancement of the MR ratio for small stripe widths can be explained by taking into account the switching thresholds of the soft (CoFe/NiFe) and hard magnetic layers (CoFe). For large stripe widths, the antiparallel magnetic state is not achieved due to the overlapping of the switching thresholds of the two ferromagnetic layers and as a result the high resistance state is not completely achieved. By decreasing the stripe width, the switching fields increases due to the size effect [9], [10], as can be observed from the inset of Fig. 2(a). Consequently, the field range for which the magnetization switching of the soft and hard magnetic layers are overlapping decreases, allowing a nearly perfect antiparallel alignment to be obtained and a higher resistance state.

Fig. 2(b) shows the magnetoresistive ratio dependence on the PSV stripe width for the transverse applied field configuration. When the magnetic field is applied perpendicular to the PSV stripe long axis, the MR ratio initially increases as the stripe width decreases. A maximum MR ratio of  $5.6\ \%$  is obtained for a width of  $40\ \mu\text{m}$ , followed by a decrease of the MR ratio by further reducing the stripe width. For widths smaller than  $40\ \mu\text{m}$  the effect of the shape anisotropy becomes more and more pronounced as can be observed from the drastic increase of the saturation fields (inset of Fig. 2(b)). Due to the increase of the saturation fields, the magnetization switching field ranges of the two ferromagnetic layers are overlapping, the antiparallel alignment is not achieved and consequently the MR ratio is decreasing.

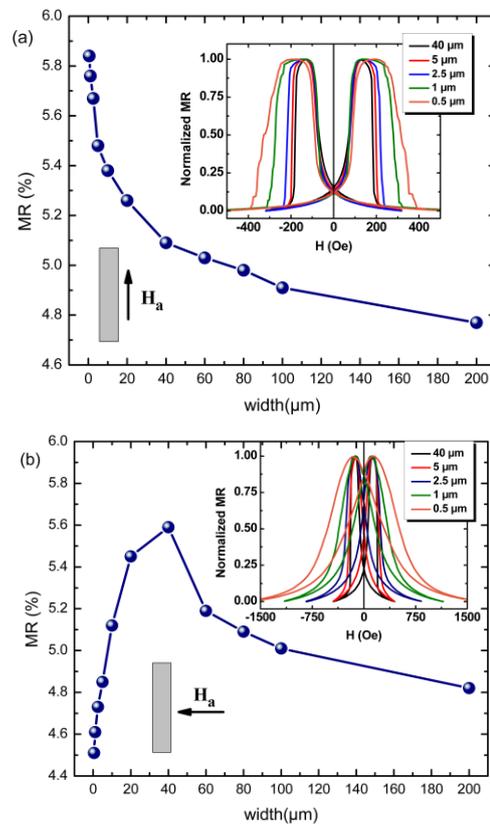


Fig. 2. Magnetoresistive ratio dependence on the stripe width for: (a) longitudinal applied field and (b) transverse applied field. In insets, the normalized MR curves for the PSV stripes having the widths of  $0.5\ \mu\text{m}$ ,  $1\ \mu\text{m}$ ,  $2.5\ \mu\text{m}$  and  $40\ \mu\text{m}$  are shown

In the transverse configuration, for the PSV stripe with the width of  $0.5\ \mu\text{m}$ , only a  $4.5\ \%$  MR ratio has been obtained, in contrast with the case of longitudinal configuration where for the  $0.5\ \mu\text{m}$  stripe the highest MR ratio has been obtained. Therefore, not only the stripe width has a strong influence on the magnetoresistance ratio but also the direction of the applied field relative to the PSV stripe.

For magnetic field sensing application, a magnetoresistive sensor must exhibit a high MR ratio and a linear response for low magnetic fields, the most

important characteristic of a magnetoresistive sensor being the sensitivity. The sensitivity of the PSV stripes has been extracted from the magnetoresistance curves, considering only the field range where the magnetoresistive response is linear ( $\pm 20$  Oe). The sensitivity dependence on the PSV stripes width, for both longitudinal and transverse applied magnetic field is presented in Fig. 3.

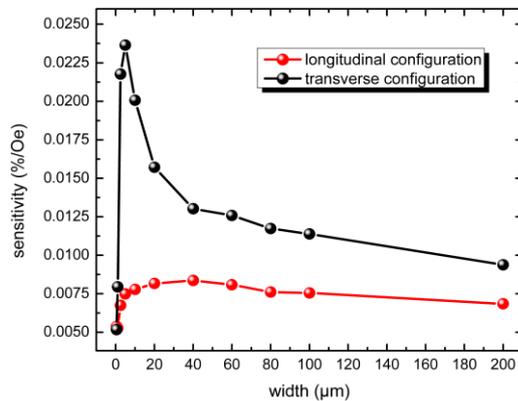


Fig. 3. Sensitivity dependence on the PSV stripe width

We can observe that for both configurations, by reducing the PSV stripe width, the sensitivity initially increases and then drastically decreases for small widths. If the magnetic field is applied in the longitudinal direction, the highest sensitivity (0.008%/Oe) is obtained for the PSV stripe with the width of 40  $\mu\text{m}$ , while for transverse applied field the highest sensitivity (0.023%/Oe) is obtained for a width of 5  $\mu\text{m}$ .

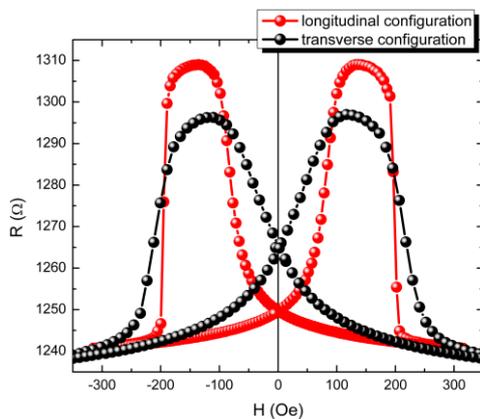


Fig. 4. MR curves obtained for the PSV stripe with the lateral dimensions of  $1000 \mu\text{m} \times 5 \mu\text{m}$

Therefore, the maximum sensitivity it is not obtained for the PSV stripe with the highest MR ratio. This is because the MR sensor sensitivity is given by the resistance variation rate in the linear field range which is in our case  $\pm 20$  Oe. From the magnetoresistance curves obtained for the PSV stripe with the lateral dimensions of  $1000 \mu\text{m} \times 5 \mu\text{m}$  (Fig. 4), we can observe that the resistance change in the low field region is higher in the case of the transverse configuration than in the longitudinal configuration, although the total MR ratio it is

higher in the latter case. Consequently, as in the case of the MR ratio, the sensitivity as well not only depends on the width of the PSV width but also on the direction of the applied field relative to the PSV stripe long axis.

#### 4. Conclusions

In this work, pseudo spin valve (PSV) magnetoresistive structures were microfabricated in order to be used in magnetic field sensing application and the effect of PSV stripes width on the magnetoresistive characteristics was studied. It was shown that by tuning the width of the PSV stripes the switching fields, the magnetoresistive ratio and the sensitivity, can be significantly enhanced. Also the effect of the applied magnetic field direction relative to the PSV stripes long axis it was investigated. The highest magnetic field sensitivity has been obtained for a PSV stripe having the width of 5  $\mu\text{m}$ , in the transverse configuration, by applying the magnetic field perpendicular to the stripe long axis.

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