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Exchange bias realignment using a laser-based direct-write technique

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Abstract

We report on selective realignment of the exchange biased magnetization direction in spintronic layer stacks using rapidly deflected focused laser radiation in a direct-write technique. Laser-based magnetic field cooling by applying either pulsed or continuous wave laser radiation was investigated. The magnetic properties of laser-based field cooled layer stacks were investigated by using magneto optical Kerr effect (MOKE) measurements. The dependencies of the processing parameters peak intensity and external magnetic field strength on the resulting exchange bias field strength were evaluated. In addition, temperature field simulations gain deeper insights into the mechanisms of laser-based field cooling.

Our results show significant influence of the laser processing regime. Field cooling induced by continuous laser radiation caused higher exchange bias field strengths, compared to pulsed laser radiation. Moreover, the external magnetic field strength affected the resulting exchange bias field strength only by irradiating low-intensity laser beams.

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1. Introduction

Since the discovery of the giant magnetoresistance (GMR) in 1988 [Binasch et al. (1989), Baibich et al. (1988)], the topic of spintronics has been of growing interest. One important field of application are magnetic field sensors, since the growing need for automatization in technical fields requires high-performance sensor technologies. Magnetic field sensors based on the GMR effect broadened the range of application due to their high sensitivity and...
compact design. Hence, they are widely used in automotive, mechanics, and computer technologies. GMR sensors are commonly based on a spin valve layer stack [Hirota et al. (2002), Dieny (1994)]. The spin valve itself consists of two ferromagnetic layers, one layer of fixed magnetic direction in order to function as reference layer, and the other one acting as the sensor layer (free layer). To pin the magnetic direction of the reference ferromagnetic layer, the exchange bias effect is used. The exchange bias effect occurs in an antiferromagnetic/ferromagnetic bilayer system when cooled in an external magnetic field through the Néel temperature [Meiklejohn and Bean (1957), Meiklejohn (1962), Nogués and Schuller (1999)]. As a result, the pinned ferromagnetic layer will be magnetized in the direction of the external magnetic field applied during the field cooling process, causing a shift of the magnetization hysteresis loop along the magnetic field strength axis. Most often the Néel temperature of the antiferromagnetic thin layer differs from the Néel temperature of the bulk material. Thus, it is usually denoted as blocking temperature.

However, manufacturing of GMR sensors requires not only precise layer deposition and structuring, but also the selective alignment of the magnetization direction of the reference layer. Therefore the layer system must be heated to the blocking temperature and cooled down in an external magnetic field. For this, laser-based magnetic field cooling has already been demonstrated by using both mask projection methods [Johnson (2003)] and static continuous wave laser irradiation [Choi et al. (2005), Choi et al. (2007)]. In a previous article we have demonstrated laser-based field cooling by using rapidly deflected focused NIR laser radiation [Berthold et al. (2014)]. Therein we applied both continuous and pulsed laser radiation. We have shown that higher laser energy input is required to realign the exchange bias by using continuous wave laser radiation, compared to irradiation of pulsed laser radiation. This means a benefit for using pulsed laser radiation. In the present study we have investigated the differences between the two process regimes more in detail with regard to the resulting exchange bias field strength. In addition, temperature field simulations were carried out to gain deeper insights into field cooling induced by either continuous or pulsed laser radiation. Furthermore, the influence of the external magnetic field strength applied during field cooling on the resulting exchange bias field strength was studied.

2. Experimental

The investigated spin-valve layer stack is shown in figure 1 (left). It consisted of a free ferromagnetic layer, a nonmagnetic spacer and a reference ferromagnetic layer. The magnetization of the latter was pinned in a direction parallel to the layer plane by the adjacent antiferromagnetic IrMn layer. Since the layer system was deposited in an external magnetic field, it revealed an initial set of the exchange bias field, as can be seen from the magnetization hysteresis loop shown in figure 1 (right). Here, the free ferromagnetic layer switches its magnetization direction already at a very low magnetic field strength, while the pinned layer switched at a much higher magnetic field strength. This is due to the shift by the exchange bias field of $H_{EB} = 81$ kA/m. The blocking temperature of the system was approximately 500 K.

Fig. 1. Schematic view of the investigated spin-valve layer stack with magnetization hysteresis loop.
The experimental setup used in this study is presented in Fig. 2 (left). A Nd:YAG laser with an emission wavelength of 1064 nm was used to initiate field cooling of the layer system. This laser system supplied both continuous wave and pulsed laser radiation. The laser beam was rapidly deflected by using a galvanometer scanner and focused by an f-theta objective with a focal length of 80 mm. The resulting focal radius (86%) of the laser beam was 12 µm. The external magnetic field was provided by an assembly consisting of two opposing permanent magnets (figure 2, right). In this way, the resulting magnetic field between the magnetic poles appeared relative homogenous. The magnetic field strength could be changed in the range between 15 and 335 kA/m by varying the distance between the magnets.

In our experiments, areas of the spin-valve layer stack were heated in the external magnetic field by deflecting the continuous and the pulsed laser beam in square areas of 200 x 200 µm² in width and length. By applying continuous wave laser radiation, the scan velocity was 1,000 mm/s and the distance between the scanned lines was 2.5 µm. Field cooling by using pulsed laser radiation was investigated by irradiating laser pulses with 100 ns pulse duration, 5 kHz pulse repetition rate, and 2.5 µm spatial pulse distance. The resulting exchange bias field strength was analyzed by subsequent magneto optical Kerr effect (MOKE) measurements.

3. Results and discussion

Figure 3 (left) shows the resulting exchange bias field strength obtained by continuous wave laser based field cooling using a scan velocity of 1,000 mm/s. The magnetic field strength and the peak intensity were varied. In the figure it can be seen that the exchange bias field was completely reversed for intensities higher than 0.5 MW/cm² without any influence of the external magnetic field strength. It can therefore be concluded, that the blocking temperature was exceeded for intensities higher than 0.5 MW/cm², i.e. the initial pinning was completely removed by heating and realigned during the cooling phase. Since there was no influence of the external magnetic field strength for this intensity range, it can be assumed, that the lowest applied magnetic field strength of 15 kA/m already saturates the unpinned ferromagnetic layer.

For continuous laser intensities lower than 0.5 MW/cm², by contrast, the external magnetic field strength affected the resulting exchange bias field strength significantly. The change of the exchange bias field compared to the initial value increased with higher external magnetic field strength and constant laser intensity levels. For example, the exchange bias was just reduced from original 81 kA/m to 26 kA/m after irradiation a continuous laser beam with an intensity of 0.35 MW/cm² and 15 kA/m external magnetic field strength. By contrast, after irradiating the same intensity at external magnetic field strengths of 55 and 150 kA/m no exchange bias was measured ($H_{EB} = 0$). Only by applying the highest external magnetic field strength of 335 kA/m, the exchange bias field was even reversed with an reduced value of -28 kA/m.

This might result from the fact, that the blocking temperature is not fixed, but reveals a distribution over a certain temperature range [Nogués and Schuller (1999)]. I.e. the pinning will be reduced continually with increasing temperature until it is completely vanished when the nominal blocking temperature is reached. From this point of view it can be assumed that individual areas of the pinned layer might become unpinned at temperatures below the
nominal blocking temperature. In this case, a higher external magnetic field strength will be required to overcome the remaining pinning and saturate the only partially pinned ferromagnetic layer. Then the already unpinned areas will be realigned during the cooling phase. As a result the average exchange bias field strength will be reduced, as can be seen in figure 3 (left) for continuous laser intensities between 0.25 and 0.3 MW/cm² and magnetic field strengths between 55 and 335 kA/m. If the laser intensity is sufficient to unpin the majority of the pinned layer, the average exchange bias field strength can even be reversed with reduced amount, as we observed for a continuous laser intensity of 0.35 MW/cm² and 335 kA/m external magnetic field strength (figure 3, left). The average exchange bias can also be extinguished \( (H_{EB} = 0) \), as can be seen in figure 3 (left) for a continuous laser intensity of 0.35 MW/cm² and external magnetic field strengths of 55 and 150 kA/m. In this case, the already realigned areas compensate the areas those still remained in the original direction.

Lower external magnetic field strengths, by contrast, are not sufficient to saturate the only partially pinned ferromagnetic layer during field cooling with low laser intensities. This in turn will cause smaller or even no change of the average exchange bias field, as can be seen in figure 3 (left) for continuous laser intensities between 0.28 and 0.35 MW/cm² and the lowest investigated external magnetic field strength of 15 kA/m.

Furthermore it can be seen in figure 3 (left), that the obtained amount of the reversed exchange bias field strength decreased for continuous laser intensities higher than 0.8 MW/cm². This might be induced by the beginning interface destruction due to overheating of the layer system, as already reported for ion irradiation in Mewes et al. (2000) and Mougin et al. (2001) as well as laser irradiation in Johnson (2003).

Figure 3 (right) shows the resulting exchange bias field strength after field cooling by applying pulsed laser radiation. It can be seen, that the exchange bias field was completely reversed after irradiating pulse peak intensities higher than 0.4 MW/cm². In this intensity range the external magnetic field strength also did not affect the resulting exchange bias field strength. An influence of the magnetic field strength was obtained only for the lowest applied intensity of 0.3 MW/cm², which was insufficient to completely realign the exchange bias. Here, the lowest magnetic field strength of 15 kA/m caused no change of the exchange bias field, while higher external magnetic field strengths resulted in reduced values of the exchange bias field strength. This is in line with the results obtained by using continuous wave laser radiation. A decrease of the resulting amount of the exchange bias field strength was observed for pulse peak intensities higher than 1.0 MW/cm², potentially due to interface destruction.

![Graph](image)

Fig. 3. Exchange bias field strength after field cooling by applying continuous wave (left) and pulsed (right) laser radiation as a function of the peak intensity. Different external magnetic field strengths were applied.
Figure 4 compares the exchange bias field strength obtained after field cooling caused by applying either pulsed or continuous wave laser radiation. The applied peak intensity was varied. It can be seen, that continuous wave laser irradiation with intensities in the range between 0.5 and 0.7 MW/cm² caused maximum amounts of the reversed exchange bias field strength, almost as large as the initial value of 81 kA/m. By contrast, irradiation of pulsed laser radiation caused reduced amounts of the exchange bias fields with a maximum of 65 kA/m.

To gain deeper insights in the mechanisms of laser-based field cooling and the differences between applying continuous and pulsed laser radiation, temperature field simulations were performed. The FEM (finite element method) software COMSOL Multiphysics was used for the calculations on the basis of the heat transfer equation:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \text{div} \left[ \lambda(T) \cdot \text{grad} T \right] + \frac{\dot{Q}}{V}$$  \hspace{1cm} (1)

Herein the heat source $\frac{\dot{Q}}{V}$ is the power density, i.e. the power input per volume element by the absorbed laser radiation. According to the Lambert Beer equation it is given by

$$\frac{\dot{Q}}{V} = -\frac{\partial I}{\partial z} = I(r,t) \cdot \alpha \cdot e^{-\alpha z}$$  \hspace{1cm} (2)

In the case of pulsed laser radiation, the spatial and temporal intensity distribution of the laser pulses can be assumed as Gaussian-shaped. By taking into account the reflectivity R, the intensity irradiated to the material is given by

$$I(r,t) = I_0 \cdot (1 - R) \cdot e^{-\frac{r^2}{w_{eq}^2}} \cdot e^{-4\ln 2 \left( \frac{r}{r_W} \right)^2}$$  \hspace{1cm} (3)

Since only a low pulse repetition rate of 5 kHz was applied, no heat accumulation is considered in this model. Therefore it is sufficient to calculate the temperature field induced by a single laser pulse. In the case of continuous wave laser radiation a moved laser beam has to be modeled. By using Cartesian coordinates the laser beam moving in the y direction with the velocity v is given by
The spintronic layer stack with a total thickness of 23 nm was modeled as a consistent metallic film with the thermal properties of tantalum. By varying the thermal properties of this film we observed no significant variance of the calculation results. This is due to the very small volume of the thin film. As a result the contribution to the heat conduction can be neglected. Among this metallic layer the 100 nm thick SiO$_2$ –film and 500 µm thick Si substrate was modeled. The optical properties reflectivity and absorption coefficients were approximated by power measurements of the reflected and transmitted laser radiation. To ascertain the absorption coefficients of the spintronic layer stack and the Si substrate, transmission measurements were performed for both, the sample with spintronic layer stack and the Si substrate. The absorption of the laser beam in the SiO$_2$ –layer could be neglected, because it is very low in the NIR wavelength range.

From the calculation results obtained the temporal temperature profiles were determined. Figure 5 shows the temporal temperature profiles as calculated at the sample surface in the center of the laser beam for either continuous (left) or pulsed (right) laser radiation. The irradiation of continuous wave laser radiation was calculated for a scan velocity of 1,000 mm/s, according to the experiments. From the left graph in figure 5 it can be seen, that the temperature curve calculated for a continuous peak intensity of 0.45 MW/cm$^2$ exceeded the blocking temperature of 500 K. This corresponds to the experimental results, which confirmed the complete exchange bias realignment for continuous laser intensities higher than 0.5 MW/cm$^2$. The temperature curves in figure 5 (right) were calculated for irradiation of one 100 ns –laser pulse with varied pulse peak intensity. It can be seen that the blocking temperature was only exceeded for the calculation with a pulse peak intensity of 0.7 MW/cm$^2$. However, this differs from the experimental results, demonstrating the complete exchange bias realignment for pulse peak intensities higher than 0.4 MW/cm$^2$. The reason for these inconsistencies is not yet clear. Despite this fact, the comparison between the calculated temperature curves for irradiation of continuous and pulsed laser radiation illustrates that the heating and cooling rate are much lower for continuous wave laser radiation. From this it can be suggested, that the significant difference of the temporal temperature profiles is one of the major reasons for the different achieved exchange bias field strengths for the two process regimes. The calculated cooling rate of about 1,800 K/µs, obtained after reaching the blocking temperature for a 100 ns laser pulse with 0.7 MW/cm$^2$ pulse peak intensity, might be too high for complete realignment of the exchange bias. As a result, the exchange bias field strength after field cooling by applying pulsed laser radiation is lower compared to the use of continuous laser radiation.

Fig. 5. Calculated temporal temperature profile at the sample surface in the center of the laser beam. Left: for irradiating continuous wave laser radiation with a scan velocity of 1,000 mm/s. Right: for irradiating one laser pulse with pulse duration 100 ns.
Furthermore there might be an influence of the spatial limitation of the area heated by one laser pulse. Because of the low pulse repetition rate of only 5 kHz, the area heated by one laser pulse is already cooled down before the next pulse irradiates after 200 µs, as can be seen from the temporal temperature curve in figure 5 (right). Hence, the exchange bias field is always realigned just in a small area. Therefore it can be supposed that the step-by-step realignment of the exchange bias obtained by irradiation of pulsed laser beams caused lower average exchange bias field strengths. In contrast, applying continuous wave laser radiation induces non-stop heating of a consistent track in the direction of laser beam movement. This consistent heating of larger areas might be another reason for higher resulting exchange bias field strengths by applying continuous wave laser radiation.

4. Conclusion

In this work we have demonstrated the realignment of the exchange biased magnetization direction in a spintronic layer stack by laser-based field cooling using a laser-based direct-write technique. In the course of this we have investigated the influence of the process regime and the external magnetic field strength on the resulting exchange bias field strength. We found, that field cooling by applying pulsed laser radiation caused reduced amounts of the exchange bias field strength compared to the initial value. In contrast, application of continuous wave laser radiation causes amounts of the exchange bias field strength almost as large as the initial value. We gained deeper insight in the differences of the two heating regimes by means of temperature field simulations. From the results obtained we concluded that much higher cooling rates by applying pulsed laser radiation do not allow the complete realignment of the exchange bias. Furthermore there might be an influence of the spatial limitation of the area heated by a single laser pulse. Hence, the exchange bias is realigned step-by-step always just in a small area and it seems conclusive, that a reduced average value of the exchange bias field strength will be achieved over a wider area.

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