Selective realignment of the exchange biased magnetization direction in spintronic layer stacks using continuous and pulsed laser radiation

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ABSTRACT

We report on selective realignment of the magnetization direction of the exchange biased ferromagnetic layer in two different spintronic layer stacks using laser radiation. The exchange bias effect occurs in an antiferromagnetic/ferromagnetic bilayer system when cooled in an external magnetic field below the Néel temperature and results in a shift of the ferromagnetic hysteresis loop with increased coercivity. The effect is utilized to pin the magnetization direction of the reference ferromagnetic layer in spin valve systems. We investigated the realignment of the pinned magnetization direction in a spin valve system with in plane exchange bias and in a Co/Pt multilayer with perpendicular exchange bias. The layer stacks were heated above the Néel temperature in a defined lateral area by using rapidly deflected laser radiation. Two different laser assisted annealing techniques were investigated applying either continuous or pulsed laser radiation. During laser annealing, the sample was subjected to an external magnetic field in order to selectively realign the magnetization direction of the pinned ferromagnetic layer. Magnetic structuring was performed by heating narrow single tracks as well as irradiating single pulses. By using a magneto optical sensor in combination with a polarization microscope, the magnetic structures have been visualized. After laser annealing of larger-scaled areas, the exchange bias field strength and the coercive field strength were analyzed using a magneto optical Kerr effect set up (MOKE). The impact of the processing parameters laser peak intensity, laser pulse duration, scan speed (continuous wave) and magnetic field strength on the resulting reversed exchange bias field was evaluated.

Keywords: exchange bias, magnetization realignment, laser annealing, field cooling, giant magneto resistance, spin valve

1. INTRODUCTION

The growing need for automatization in technical fields requires high-performance sensor technologies. Particular importance can be attached to magnetic field sensors because of their frequent application in automotive, mechanical and computer technologies (read heads in modern magnetic recording). In recent years, GMR (giant magneto-resistance) sensors have been increasingly established due to their high sensitivity and compact design. Hence, the GMR effect and manufacturing techniques for GMR sensors are of great interest in research and development. GMR sensors are commonly based on a spin valve layer stack \cite{1, 2}. 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 \cite{3-5}. 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 bulk Néel temperature. Thus, it is usually denoted as blocking temperature.

Manufacturing of GMR sensors requires not only precise layer deposition and structuring, but also the specific and local 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 \cite{6} and static continuous wave laser irradiation \cite{7, 8}. In this work, laser-based field cooling of spintronic layer stacks in a magnetic field is investigated by using rapidly
deflected focused laser radiation. The benefit of this direct writing method is the highly defined realignment of the magnetic direction of spintronic layer stacks in small lateral areas of any shape.

2. EXPERIMENTAL

2.1 Material

Two different spintronic systems were investigated in this work, a complete spin valve layer system with in-plane exchange bias and a Co/Pt multilayer system with out of plane exchange bias. The former consists of a free ferromagnetic layer, a nonmagnetic spacer and a reference ferromagnetic layer (figure 1a). The reference ferromagnetic layer can be magnetically pinned in a direction parallel to the layer plane by the adjacent antiferromagnetic IrMn layer due to the exchange bias effect. Since the layer system was deposited in an external magnetic field, it revealed an initial set exchange bias, as can be seen from the related magnetization hysteresis loop given in figure 1 a). Here, the free ferromagnetic layer switches its magnetization direction already at a very low magnetic field strength, while the pinned layer switches not until a much higher magnetic field strength. This is due to the shift by the exchange bias filed of \( H_{EB} = 81 \text{ kA/m} \). Furthermore the coercive field strength \( H_{Coer} \) of the pinned layer is increased to 7.8 kA/m due to the exchange bias effect. The related blocking temperature for this system was approximately 500 K.

The second layer system with out of plane exchange bias embodies no entire spin valve but only an exchange bias system (figure 1b). The ferromagnetic Co/Pt multilayer reveals perpendicular anisotropy. Hence, the magnetization direction can be pinned perpendicular to the layer plane due to the adjacent antiferromagnetic IrMn layer by magnetic field cooling in a perpendicular magnetic field strong enough to saturate the Co/Pt multilayer. This layer system was deposited in an external magnetic field as well, to adjust the initial exchange bias field, as can be seen from the magnetization hysteresis loop in figure 1 b). In this figure, the hysteresis loop exhibits just the magnetization switching of the pinned Co/Pt multilayer, which is due to the missing free layer. For this the exchange bias field strength is 23 kA/m. Furthermore the layer system revealed a coercive field strength of 24 kA/m. The related blocking temperature was approximately 400 K.

2.2 Experimental setup

The spintronic layer systems were locally heated by using a Nd:YAG laser. The laser has an emission wavelength of 1064 nm and can operate either in the continuous wave mode or in the q-switched mode. By changing the pulse repetition rate the pulse duration could be varied between 62 and 202 ns. The laser beam was rapidly deflected by using a galvanometer scanner and focused by the use of an f-theta optic with a focal length of 80 mm (figure 2). The resulting \( 1/e^2 \) radius of the focused laser beam was 12 µm.

![Figure 1. Schematic view of the investigated layer stacks with related magnetization hysteresis loops. a) complete spin valve layer system with in-plane exchange bias. b) Co/Pt multilayer exchange bias system with out of plane exchange bias.](image-url)
Permanent magnets were used to provide the external magnetic field during the laser annealing process. For the realignment of the in-plane exchange bias, a setup with two opposing magnets was utilized (figure 3, left). In this way, the resulting magnetic field inbetween the magnetic poles appears relative homogenous and the magnetic field strength could be changed by varying the distance between the magnets. By contrast, the magnetic field for the manipulation of the out of plane exchange bias was provided by one permanent magnet. This magnet was placed underneath the sample, thus the sample plane was penetrated perpendicularly by the permanent magnetic field (figure 3, right). During the field cooling process, the external magnetic field was oriented in opposite direction to the initially pinned magnetization direction, in order to reverse the exchange bias field.

**2.3 Experimental procedure**

In a fundamental study, the spatial resolution limits of the exchange bias realignment were determined by means of field cooling of laser processed areas. Using continuous wave laser radiation, single narrow tracks were heated by rapid deflection of the focused laser beam (figure 4, left). By applying pulsed laser radiation, small areas were magnetically realigned by either single laser pulses (figure 4, center) or single tracks obtained by highly overlapping laser pulses (figure 4, right). The investigations were carried out on both the in-plane and the out-of-plane exchange bias system.

**Figure 2.** Experimental setup.

**Figure 3.** Magnetic field configuration. left: in plane. right: out of plane.

**Figure 4.** Process scheme of magnetic structuring of the out-of-plane exchange bias system using single laser pulses (center) as well as single tracks obtained with continuous wave (left) and pulsed (right) laser radiation, initial magnetization direction and external magnetic field perpendicular to the sample surface are presented.
In addition, lager-scaled areas were heated in the external magnetic field by scanning a square area of 200 x 200 µm² with adequate high spatial pulse overlap or track overlap (figure 5). Continuous wave and pulsed laser radiation were irradiated on both layer systems on interest. The resulting exchange bias field strength and coercive field strength were determined by subsequent magneto optical Kerr effect (MOKE) measurements.

In our study, laser pulses of two different durations (62 ns and 167 ns) were irradiated on the out-of-plane exchange bias system. This was to investigate the impact of the pulse duration on the change of the exchange bias field strength. By contrast, continuous wave laser radiation was irradiated to the sample using two different scan velocities, 1000 mm/s and 4000 mm/s. During these experiments the external magnetic field strength was kept constant of 290 kA/m. A more detailed study was carried out on the in-plane exchange bias system. Here the pulse duration and magnetic field strength was varied between 62 ns, 105 ns, 167 ns and 202 ns, as well as 15 kA/m, 55 kA/m, 150 kA/m and 335 kA/m, respectively. Moreover, continuous wave laser radiation was irradiated with two scan velocities, 100 mm/s and 1000 mm/s.

![Figure 5. Process scheme of magnetic realignment of larger areas (200 x 200 µm²) by scanning with the focused laser beam with high spatial pulse overlap or track overlap.]

2.4 Analysis

Two different methods of analysis were applied. The studies of magnetic realignment by single tracks and single pulses were analyzed by using a magneto optical sensor based on the Faraday effect. The sensor is composed of a thin magneto optical single crystal attached to an objective adapter. The sensor was mounted to a polarization microscope in the focal plane. Thus, the sensor was placed on the sample surface when the objective has been focused. By this way, the sensor was penetrated by the magnetic field lines passing out and reentering the sample surface, schematically shown in figure 6. The linear polarized light of the microscope passes through the sensor. At sample areas where the magnetic field lines pass out or reenter the surface, the polarization plane of the imaging light is rotated due to the Faraday effect. By applying a polarization analyzer in the optical path of the microscope, the position dependent rotation of the polarization plane was visualized. As a result, this method visualized the magnetic structuring by bright and dark areas in the image.

![Figure 6. Principle of operation of the magneto optical sensor.]

Enhanced informations about the resulting magnetic properties were obtained by utilizing magneto optical Kerr effect (MOKE) measurements. The Kerr effect describes the rotation of the polarization plane of a linear polarized measuring
laser beam depending on the magnetization of the reflecting sample (figure 7). By using this technique, the magnetization hysteresis loop can be detected at a certain area of the sample. Therefore a varying magnetic field was provided and the resulting rotation of the polarization plane is recorded, according to the related magnetization. In our study, the exchange bias field strength and the coercive field strength were determined from these magnetization hysteresis loops. The measurements were performed using a MOKE measurement setup, located at the Institute of Physics, Chemnitz, University of Technology (working group Albrecht).

![Figure 7. Principle of operation of the MOKE measurements.](image)

3. RESULTS AND DISCUSSION

3.1 Magnetic realignment by using single laser pulses and single laser tracks

*Layer system with out of plane exchange bias*

Figure 8 shows the laser-assisted realigned magnetic structures processed on the out-of-plane exchange bias system. In this figure, visualization of the laser processed areas proves the laser-assisted magnetic realignment. This is because the images were captured by using the polarization microscope / magneto optical sensor analysis assembly. From figure 8 a) it can be derived that the realignment of pinning direction has been initiated by irradiation of single laser pulses of 0.6 MW/cm² peak intensity, the pulse duration was 62 ns. Moreover, it can be seen in figure 8 a) and b) that the spot diameter of the magnetically reversed spots increased with increasing laser peak intensity to approximately 10 µm. However, starting from a pulse peak intensity of 2.3 MW/cm², a further contrast appears in the spot center of the spots. This suggests material overheating and thus destruction of the layer substrate in the center, caused by the Gaussian intensity profile.

Figure 8 c) shows magnetically realigned lines, produced by the irradiation of highly overlapping laser pulses of 2 µm pulse to pulse distance. A pulse peak intensity of 0.2 MW/cm² was sufficiently high to reverse the magnetization of the out-of-plane exchange bias system. A further contrast can be observed in the figure for laser pulses of 1.1 MW/cm² and higher, suggesting local overheating in the center of the laser processed lines.

![Figure 8. Magnetic structures on the out-of-plane exchange bias system, visualized by using the magneto optical sensor. a) and b): small circular areas, magnetically realigned by single pulses with different intensities. c) narrow lines, magnetically realigned by single tracks of the pulsed laser beam with high spatial pulse overlap (pulse distance of 2 µm).](image)
In addition to pulsed laser processing, magnetically realigned lines have been also fabricated on the out-of-plane exchange bias substrate by irradiating continuous wave laser radiation. To initiate realignment of the exchange bias by using this processing regime, the threshold values have been determined depending on the scan velocity of the laser beam of either 0.20 MW/cm² or 0.25 MW/cm² at 100 mm/s and 4000 mm/s, respectively. Furthermore it was found that intensities greater than 0.75 MW/cm² result in overheating at the line center, potentially causing damage to the layer stack.

Spin valve layer system with in-plane exchange bias

For the in-plane exchange bias system, beginning of magnetical realignment of the laser processed areas was observed for single pulses of 62 ns pulse duration and 0.8 MW/cm² peak intensity. Local overheating accompanied by damage to the layer stack was ascertained in the center of the local sphere of influence by irradiating laser pulses with intensities larger than 2.5 MW/cm². The magnetic realignment of narrow lines by single tracks of pulsed laser radiation with high pulse overlap (pulse distance of 2 µm) was observed starting from an intensity of 0.5 MW/cm². Intensities greater than 1.7 MW/cm² caused overheating in the line center. By applying continuous wave laser radiation at scan velocities between 100 mm/s and 4000 mm/s, magnetically realigned single tracks were achieved starting from intensities between 0.3 MW/cm² and 0.4 MW/cm², respectively. Thus, the required intensities for magnetic structuring were higher compared to the process on the out of plane exchange bias system. This is in line with expectations, since the blocking temperature of the spin valve layer system with in plane exchange bias was higher.

3.2 Magnetic realignment of larger areas

In another approach, laser-assisted magnetic realignment of larger areas was investigated. For this, square areas have been processed by scanning the focused laser beam (pulsed, continuous wave) across the substrates. The impact of the laser processing parameters on the magnetic realignment was analyzed by MOKE measurements.

Layer system with out of plane exchange bias

Figure 9 shows exemplarily magnetization hysteresis loops after field cooling induced by laser pulses of 167 ns pulse duration and pulse peak intensities ranging between 0.2 MW/cm², 0.3 MW/cm², and 1.1 MW/cm². The figure 9 a) points out that field cooling based on irradiating low intensity pulses of 0.2 MW/cm² initiated only increased coercive field strength. It can thus be concluded, that the laser-induced temperature increase in the film was not sufficient to reach the blocking temperature. In figure 9 b) it is shown that laser irradiation of pulses with the higher intensity of 0.3 MW/cm² was sufficiently high to change the sign of the exchange bias field and thus to realign the pinned magnetization direction. The considerably higher pulse peak intensity of 1.1 MW/cm², by contrast, caused the destruction of the layer stack. This is indicated by the distorted magnetization hysteresis loop shown in figure 9 c).

Figure 9. Magnetization hysteresis loops of the out-of-plane exchange bias system after field cooling based on irradiating pulsed laser radiation. Field cooling with pulse duration of 167 ns and different pulse peak intensities. The initial hysteresis loop is marked as grey curve.
Figure 10 a) depicts the resulting exchange bias field strength as a function of the applied pulse peak intensity for the two investigated pulse durations. It can be seen, that irradiation of laser pulses of 167 ns and 0.3 MW/cm² pulse peak intensity caused a change of sign of the exchange bias field strength. Thus the pinned magnetization direction was reversed. To generate this magnetical realignment with shorter laser pulses of 62 ns, a higher pulse peak intensity of 0.4 MW/cm² was required. Moreover it can be seen in the figure 10 a), that pulse peak intensities larger than 2.0 MW/cm² caused decreased exchange bias field strength, potentially indicating damage to the layer system.

Figure 10 b) shows the resulting coercive field strength after the field cooling as a function of the pulse peak intensity. Laser pulses of two different pulse durations (62 ns, 167 ns) were investigated. For laser intensities in the range up to 1 MW/cm² it can be seen that laser-assisted resetting of the exchange bias direction caused increased coercive field strengths, compared to the marked reference value. For this generation of further pinning sites such as grain boundaries or small defects in the antiferromagnetic as well as ferromagnetic layer by laser heating can be suggested. As a result, the number of domains will be increased, which is in accordance to the Domain State Model [9,10,11], leading to higher coercive field strengths. Pulse peak intensities greater than 1.0 MW/cm² caused decreased coercive field strengths accompanied with distorted magnetization hysteresis loops (figure 9 c). This indicates already incipient destruction of the layer system.

In addition, field cooling based on irradiating continuous wave laser radiation was investigated. Two different scan velocities of 1000 mm/s and 4000 mm/s were applied. Figure 11 a) depicts the resulting exchange bias field strength as a function of the laser beam intensity for the two different scan velocities. The figure gives evidence that an intensity of 0.3 MW/cm² lead to a complete realignment of the exchange bias field and thus of the pinned magnetization direction. Figure 11 b) shows the resulting coercive field strength as a function of the laser beam intensity. Initially the increase of the coercive field strength after field cooling process can be observed with increasing intensity, according to the Domain State Modell. Starting from the peak intensity of 0.6 MW/cm² the coercive field strength decreases again, indicating incipient destruction.
Figure 11. Resulting exchange bias field (a) and resulting coercive field strength (b) as a function of the applied laser peak intensity, after the field cooling process by continuous wave laser radiation with two different scan velocities, on the out-of-plane exchange bias system. The initial values are marked as dotted line.

Spin valve layer system with in plane exchange bias

Laser assisted magnetic realignment of the in-plane exchange bias system has been investigated more in detail with particular focus on both the pulse duration and the external magnetic field strength. Figure 12 shows exemplary magnetization hysteresis loops after the field cooling based on irradiating pulsed laser radiation. Laser pulses of 167 ns pulse duration and different peak intensities ranging between 0.3 MW/cm² and 2.5 MW/cm² were applied. The magnetic field strength was 335 kA/m. It can be seen, that a low pulse peak intensity of 0.3 MW/cm² caused a reduced exchange bias field strength (figure 12a). Moreover, the switching of the pinned layer revealed a larger switching field distribution, compared to the initial curve. This can be suggested to the different temperature areas as a result of the Gaussian intensity profile of the laser beam. Potentially the highest temperature, reached in the center of the local sphere of influence, was already sufficiently high to attenuate or erase the pinning. In these regions the magnetization switches already at lower magnetic field strengths. However, in the colder outer regions of the local sphere of influence the exchange bias was hardly affected. Thus, the magnetization of these areas switches at slightly higher magnetic field strengths. Hence, the switching of the pinned layer was distributed over a wider magnetic field strength range, leading to a lower gradient.

By irradiating laser pulses of higher pulse peak intensity of 0.4 MW/cm², the sign of the exchange bias field was reversed (figure 12b). Furthermore it can be seen that the amount of exchange bias field strength and the gradient of the switching process were reduced. For this, as already suggested for the lower intensity, inhomogeneous temperature areas will potentially lead to this broad distribution of exchange bias field strength depending on the locally reached temperature due to the laser penetration having Gaussian intensity profile.

The field cooling process following laser irradiation of pulses of 0.5 MW/cm² caused the complete realignment of the exchange bias field, as shown in figure 12c. Figure 12d), by contrast, presents exemplarily the magnetization hysteresis loop for laser pulses of higher intensities. For pulses of 2.5 MW/cm² the decrease of the exchange bias field is obvious that might be caused by destruction of the layer system.
Field cooling with pulse duration of 167 ns and different pulse peak intensities. External magnetic field strength of 335 kA/m. The initial hysteresis loop is marked as grey curve.

Figure 12. Magnetization hysteresis loops of the in-plane exchange bias system after field cooling with pulsed laser radiation.

Figure 13 a) summarizes the resulting exchange bias field strength as a function of the pulse peak intensity. The pulse duration was varied while the influencing magnetic field strength was kept constant of 15 kA/m. For pulses with the pulse duration of 105 ns, 167 ns and 202 ns it can be seen that a pulse peak intensity of 0.4 MW/cm$^2$ was sufficiently high for complete realignment of the exchange bias field. Only by applying the shortest investigated pulse duration of 62 ns, a higher pulse peak intensity of 0.6 MW/cm$^2$ was required.

Moreover, it is conspicuous in this figure that the amount of the realigned exchange bias field reached not the initial value of 81 kA/m. The explanation therefore can be suggested as follows: (I) The cooling phase might be too short for a complete realignment of the exchange bias, since the short pulse durations cause high cooling rates. However, further work is needed here. (II) The spatial limitation of the area heated by one laser pulse might influence the resulting exchange bias field strength. As a result of the low pulse repetition rate (1 kHz – 10 kHz) used in this study, the laser heated zone is already cooled down when the next pulse irradiates. Hence, the antiferromagnetic order was realigned always just in a very small lateral region. It can be suggested, that step by step realignment due to irradiation of pulsed laser beams will cause a lower average value of the exchange bias.
Figure 13. Resulting exchange bias field as a function of the applied pulse peak intensity after the field cooling process by pulsed laser radiation, on the in-plane exchange bias system. a) For the different applied pulse durations at external magnetic field strength of 15 kA/m. b) For the different applied magnetic field strengths at pulse duration of 167 ns.

Furthermore, the impact of the applied external magnetic field strength on the resulting exchange bias field strength was investigated. Figure 13 b) indicates no significant influence of the magnetic field strength. From these results it can be concluded that the applied magnetic field strengths is in the range of saturation of the ferromagnetic layer.

Figure 14 shows the resulting coercive field strength as a function of the pulse peak intensity for the different applied magnetic field strengths. For laser intensities in the range up to 1.3 MW/cm² the increase of the coercive field strength can be observed. With higher intensities, by contrast, the coercive field strength decreased. For this, incipient destruction of the layer system can be assumed. As expected it can also be seen in this figure that the coercive field strength is not affected by the external magnetic field strength by taking measurement errors into account.

The laser-assisted magnetic realignment on square areas was also investigated by applying continuous wave laser radiation. Figure 15 depicts the resulting exchange bias field strength as a function of the laser beam intensity for different external magnetic field strengths and scan velocities (100 mm/s and 1000 mm/s). Figure 15 a) shows that complete realignment of the exchange bias field has been obtained by using pulses with intensities higher than 0.4 MW/cm². Furthermore, for the lower intensities it can be seen that the external magnetic field strength affected the exchange bias field strength. With higher magnetic field strength and pulses in the same intensity range there was a larger change of the exchange bias field. The amount of the reversed exchange bias field strength reached approximately the initial value, which is in contrast to pulsed laser heating. The explanation for this can be seen in the lower cooling rates that will be potentially induced by the continuous wave laser radiation and larger contiguously heated areas.
In figure 15 b) it can be seen, that laser beam intensities of 0.4 MW/cm$^2$ and 0.5 MW/cm$^2$ irradiated with scan velocities of 100 mm/s and 1000 mm/s, respectively, were sufficiently high to realign the exchange bias field completely. Thus, the required intensities were in the same range like those by applying pulsed laser radiation.

Figure 15. Resulting exchange bias field as a function of the applied laser beam intensity after the field cooling process by continuous wave laser radiation, on the in-plane exchange bias system. a) For the different applied magnetic field strengths at a scan velocity of 1000 mm/s. b) For the two applied scan velocities at an external magnetic field strength of 15 kA/m.

4. CONCLUSION

In this work, magnetic reversal of an exchange biased ferromagnetic layer was investigated by using magnetic field cooling based on irradiating rapidly scanned focused laser radiation. We demonstrated magnetic structuring by focused laser radiation with high lateral resolution. Narrow lines with a width in the range of 5 – 15 µm were magnetically realigned by pulsed laser radiation with high spatial pulse overlap as well as rapidly scanned continuous wave laser radiation. We also achieved the magnetization reversal in circular regions with diameters of several µm by heating with single pulses. These magnetic structures have been visualized by the use of a magneto optical sensor based on the Faraday effect. Furthermore, laser assisted field cooling was applied on areas of 200 x 200 µm$^2$ in order to analyze the resulting exchange bias field strength and the coercive field strength by MOKE measurements. By applying pulsed laser radiation the field cooling process resulted in lower amounts of the exchange bias field strength, compared to the initial value. This might be affected by high cooling rates as well as the spatial limitation of heating by applying short laser pulses. These assumptions are conclusive with the higher amounts of the exchange bias field strength obtained after field cooling based on irradiating continuous wave laser radiation.

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