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Robust giant magnetoresistance material system for magnetic sensors

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A new, robust giant magnetoresistance (GMR) material system is described that comprises an exchange-biased artificial antiferromagnet. For the exchange biasing $Ir_{18}Mn_{82}$ is used because of its high blocking temperature. Experiments have demonstrated that this material can withstand magnetic fields larger than 150 kA/m and annealing at temperatures above 275 °C without irreversible damage. At higher temperatures the GMR effect starts to decrease due to atomic diffusion; the exchange-biasing effect, however, does not disappear, which means that this is no longer the limiting factor. The excellent magnetic and thermal robustness, combined with the unambiguous asymmetric magnetoresistance curve, makes this GMR material system very suitable for application in (e.g., automotive) sensors.
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I. INTRODUCTION

Much effort has been put in the development of giant magnetoresistance (GMR) materials for application in read heads.[1] Far less attention has, however, been paid to the very large application area of other types of magnetic sensors, including e.g., angle, rotation speed, and position sensors. Nevertheless, also here the GMR effect can offer some attractive advantages, like the high magnetoresistance ratio and the 360° period of the angle dependence.

The material requirements for these sensors, that are mainly used in automotive and industrial environments are, however, very different from those for read heads. Robustness at high temperatures (up to ~200 °C) and in large magnetic fields (up to ~100 kA/m) is often a prerequisite. Furthermore, the output signal should be large and unambiguous. Since in many cases Wheatstone-bridge configurations are desired in order to reduce the effect of temperature variations, it should be possible to realize GMR elements with opposite signs of the resistance change caused by an applied magnetic field. This means that an asymmetric magnetoresistance curve is preferred.

In this article, we describe the composition and properties of a new GMR material system that can fulfil these requirements.

II. MATERIAL COMPOSITION

In a conventional spin valve[2,3] both the magnetic-field and temperature range for operation is too narrow for sensor applications. In particular, the exchange biasing is usually a limiting factor. As an alternative it has been proposed to use an artificial antiferromagnet (AAF) instead of exchange biasing.[4] However, this has the important disadvantage that the magnetoresistance curve is not unambiguous, since the magnetizations in the AAF can be flipped in a field. This restricts the allowed field range to a few tens of kA/m, which is smaller than the field near a typical permanent magnet. Another option is the use of antiferromagnetically coupled multilayers.[5] For these multilayers the resulting magnetoresistance curve is, however, principally symmetric around zero field, which complicates the realization of a full Wheatstone bridge. Furthermore, since the magnetizations of all magnetic layers in the multilayer can rotate, it cannot be used directly in an angle sensor like the other mentioned GMR materials.

In order to achieve both an excellent thermal and magnetic stability and an unambiguous asymmetric magnetoresistance effect, we chose to use an exchange-biased AAF. Ir–Mn is preferred as the exchange-biasing material because of its high blocking temperature (around 560 K).[6] An Ir-content of around 20% seems to be optimal for exchange biasing; for the experiments described in this article, $Ir_{18}Mn_{82}$ was used. For the AAF a $Co_{90}Fe_{10}$/Ru/$Co_{90}Fe_{10}$ sandwich is used, because of the strong exchange coupling that Ru can provide and the possibility to induce uniaxial in-plane anisotropy in $Co_{90}Fe_{10}$ (in contrast to e.g., Co).

To minimize the possibility of diffusion at elevated temperatures, we have avoided Ni at the interfaces with the Cu spacer layer by inserting a thin $Co_{90}Fe_{10}$ layer between $Ni_{80}Fe_{20}$ and Cu. This additionally increases the GMR effect.

Earlier experiments with $Fe_{50}Mn_{50}$-based spin valves showed that the exchange-biasing field (and the GMR ratio) is larger for the inverted than for the conventional layer order.[7] Since we made the same observations for the new material system, an inverted layer stack, in which the Ir–Mn layer is below the AAF, has been chosen. Analyses by transmission electron microscopy (TEM) have shown that also for Ir–Mn the (111) texture is advantageous for optimal exchange biasing. We found that this can be obtained by using a buffer layer consisting of 3.5 nm Ta and 2.0 nm $Ni_{80}Fe_{20}$. Remarkably, it turned out to be important for good exchange biasing to use not too thick Ir–Mn layers: while 10 nm Ir–Mn shows an excellent (111) texture, 30 nm Ir–Mn has partially a random texture and a less stable exchange-biasing effect.[6]

Finally, a Ta cap layer is used to protect the film. Taking all these considerations into account, our preferred GMR material system has a composition as presented in Fig. 1.

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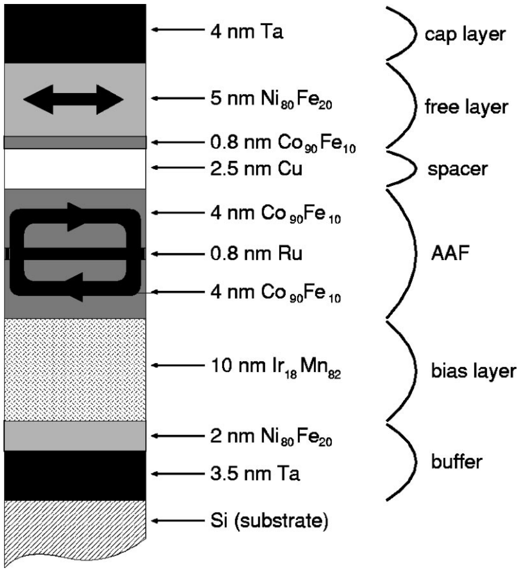

FIG. 1. Schematic view of the studied GMR system that comprises an exchange-biased artificial antiferromagnet.

III. MATERIAL CHARACTERISTICS

All samples were grown at room temperature by dc magnetron sputtering (base pressure $\sim 10^{-8}$ mbar) on $4 \times 12\,mm^2$ Si(100) substrates. During deposition, a field of $\sim$20 kA/m was applied along the long axes of the substrates to induce anisotropy. The magnetoresistance of the spin valves with an exchange-biased AAF was measured in a four-terminal configuration at room temperature. For the field-anneal experiments both rapid thermal processing (RTP) and annealing in a tube furnace were used.

The magnetoresistance curve of a 3.5 nm Ta/2 nm $Ni_{80}Fe_{20}$/10 nm $Ir_{18}Mn_{82}$/4 nm $Co_{90}Fe_{10}$/0.8 nm Ru/4 nm $Co_{90}Fe_{10}$/2.5 nm Cu/0.8 nm $Co_{90}Fe_{10}$/5 nm $Ni_{80}Fe_{20}$/4 nm Ta film is shown in Fig. 2 (solid line). The step-like magnetoresistance curve shows a GMR ratio of $\sim$7%, which is much larger than what is typically obtained with the AMR effect of a 20 nm $Ni_{80}Fe_{20}$ film (dashed line). For comparison, a magnetoresistance curve of a GMR stack with an AAF without exchange biasing (3.5 nm Ta/2 nm $Ni_{80}Fe_{20}$/3.5 nm $Co_{90}Fe_{10}$/0.8 nm Ru/3.5 nm $Co_{90}Fe_{10}$/2.5 nm Cu/0.8 nm $Co_{90}Fe_{10}$/5 nm $Ni_{80}Fe_{20}$/4 nm Ta) is included in the same figure (dot-dashed line). The field range of this multilayer was certainly not optimized, but the undesired flipping of the output at higher fields is inherent to this kind of material system.[8] The magnetic stability of our exchange-biased AAF is excellent; we never observed flipping, although fields up to 150 kA/m were applied (see Fig. 3). If we compare this with a conventional spin valve that was studied earlier for read head applications (3.5 nm Ta/8 nm $Ni_{80}Fe_{20}$/2.5 nm Cu/6 nm $Ni_{80}Fe_{20}$/10 nm $Fe_{50}Mn_{50}$/4 nm Ta; dashed line in Fig. 3), the field range over which the resistance change is larger than zero is enlarged by more than a factor of 7, while the GMR ratio is also significantly larger. The obtained extension of the magnetic-field range can be explained by the (ideally) zero net magnetic moment of the AAF.

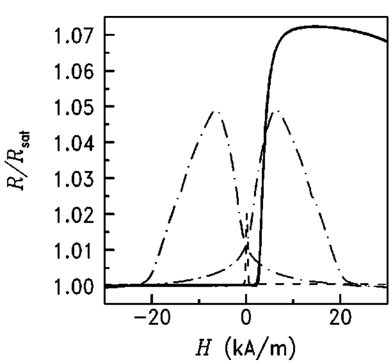

FIG. 2. Comparison of the magnetoresistance curves of the GMR material system from Fig. 1 (solid line), a GMR stack with an unbiased AAF (3.5 nm Ta/2 nm $Ni_{80}Fe_{20}$/3.5 nm $Co_{90}Fe_{10}$/0.8 nm Ru/3.5 nm $Co_{90}Fe_{10}$/2.5 nm Cu/0.8 nm $Co_{90}Fe_{10}$/5 nm $Ni_{80}Fe_{20}$/4 nm Ta; dot-dashed line) and a 3.5 nm Ta/20 nm $Ni_{80}Fe_{20}$/5 nm film (dashed line).

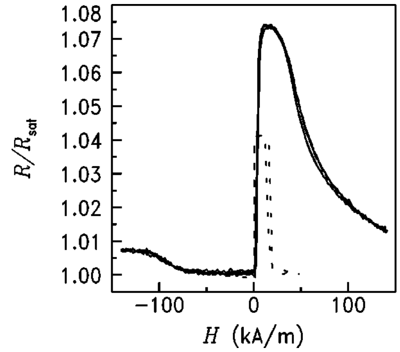

FIG. 3. Magnetoresistance curve of the GMR material system from Fig. 1 over a broad field range (solid line); for comparison a magnetoresistance curve of a conventional spin valve is included (3.5 nm Ta/8 nm $Ni_{80}Fe_{20}$/2.5 nm Cu/6 nm $Ni_{80}Fe_{20}$/10 nm $Fe_{50}Mn_{50}$/4 nm Ta; dashed line).

In order to test the thermal stability of the GMR stack with an exchange-biased AAF several annealing experiments have been done. GMR films were subsequently annealed for one minute at 250, 275, 300, 325, 350, 375, 400, 425, and 450 °C in an N_2/H_2 atmosphere using RTP. During annealing, a magnetic field of $\approx$50 kA/m was applied in the plane of the film but perpendicular to the field during deposition. After deposition and after each anneal treatment, the magnetoresistance was measured at room temperature, both with the applied magnetic field parallel and perpendicular to the field during deposition. The results for a film with the composition of Fig. 1 are shown in Fig. 4. After the first anneal, the GMR ratio turns out to be increased; for temperatures of 300 °C and above the effect gradually decreases. Although the field during annealing was applied perpendicular to the original exchange-biasing direction, this direction has not been changed. This is indicated by the fact that up to the last anneal at 450 °C, the typical step-like magnetoresistance curve persists. This has been confirmed by measuring the magnetoresistance with a field applied parallel to the field during annealing: these measurements only showed essentially symmetric dip-shaped curves. This excellent thermal stability of the pinned layer could only be obtained by the *combination* of Ir–Mn with an AAF. In this respect it is interesting to note that the exchange-biasing direction of an Ir–Mn-based spin valve with a single 6 nm Co–Fe layer

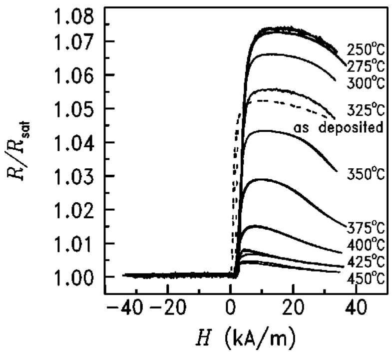

FIG. 4. Magnetoresistance curves of the GMR material system from Fig. 1 as-deposited (dashed line) and after the anneal treatments at the indicated temperatures (solid lines); the measuring field is applied parallel to the original exchange-biasing direction.

instead of the AAF could easily be rotated by the anneal treatment at 350 °C (due to the nonzero net moment).

Since the GMR effect has diminished at the highest temperatures, this suggests that the exchange biasing is so stable that structural degeneration of the material occurs before magnetic degeneration. To check this a sample that had been used for the RTP experiments and an identical sample that had not been annealed were analysed. Sputtering Auger electron spectroscopy (AES) showed that indeed some diffusion had taken place: Co was observed in the Ni–Fe layer, and Mn in the Co–Fe and Cu layers. Rutherford backscattering spectroscopy showed that the interfaces were still sharp; in particular the 0.8 nm Ru layer (which was considered the most critical one because of its small thickness) looked unchanged despite all anneal treatments.

To get better insight in the occurrence of diffusion, Ir–Mn/Co–Fe bilayers were annealed in a tube furnace for 2 h at respectively 240, 270, 320, and 400 °C and compared with an as-deposited sample using AES. No change was observed in the samples that were annealed at 240 and 270 °C; in the samples that were annealed at 320 and 400 °C Co was found in the Ir–Mn layer. These results are consistent with the RTP results suggesting that diffusion starts from around 300 °C (on the investigated time scales). This also indicates that limited amounts of Co in Ir–Mn do not affect the exchange biasing.

Finally, we also performed TEM on a complete GMR stack with exchange-biased AAF while it was *in situ* heated up to 450 °C. The good (111) texture remained unchanged, which means that this prerequisite for exchange biasing is still present at this very high temperature.

IV. CONCLUSIONS

We have described a robust GMR material system based on an exchange-biased artificial antiferromagnet. For the exchange biasing $Ir_{18}Mn_{82}$ has been used. Experiments have shown that this material can withstand magnetic fields >150 kA/m and annealing at temperatures >275 °C without irreversible damage. At higher temperatures the GMR effect starts to decrease due to atomic diffusion; the exchange biasing, however, does not disappear and neither rotate. This means that exchange biasing is no longer the limiting factor for the thermal stability. The outstanding thermal and magnetic robustness, combined with an unambiguous asymmetric magnetoresistance curve, make this GMR material system very suitable for application in (e.g., automotive) sensors.

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