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Magnetic Thermal Annealing: An Effective Process to Enhance the Performance of Magnetic Devices and Materials

When determining the strength, ductility, and hardness of a solid, certain structural factors need to be considered. Lattice and shape deformities in a material can significantly degrade its quality, and removing these anomalies in structure is necessary in order to achieve a high quality material and performance.

Thermal annealing is a common technique used to strengthen a solid, such as metal or glass, by raising, maintaining, and then slowly reducing its temperature. Annealing allows the atoms inside of a solid to diffuse more easily to find their proper locations, and maintaining a solid at a high temperature lets it achieve equilibrium, eliminating many structural imperfections that would otherwise reduce its utility.

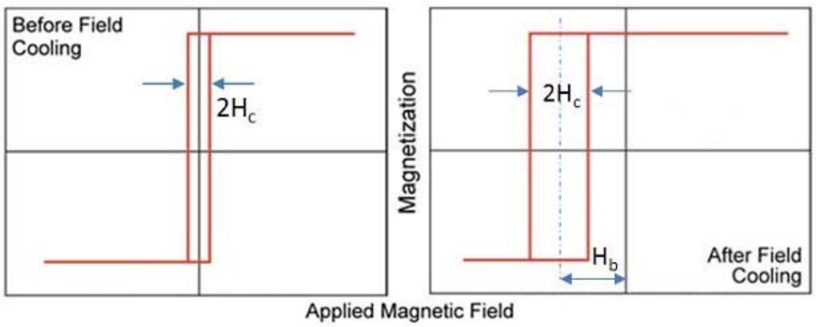

Fig. 1: Hysteresis loops demonstrating the appearance of exchange bias after magnetic thermal annealing

Annealing has been a widely used technique in metallurgy for quite some time. However, a relatively new technique, called magnetic thermal annealing, puts a new spin on this age-old method. The major difference between the two heat treatments is that in magnetic annealing, an external magnetic field is applied during the annealing process. This has some very interesting effects, especially on ferromagnetic (FM) and antiferromagnetic (AFM) materials.

One of the most important effects of magnetic thermal annealing is the reorientation of the easy axis in a FM material, or the axis of spontaneous magnetization vector. In any FM material, the easy axis is primarily determined by the lattice structure (in some cases, by the shape or the internal strain of a solid). For example, if the lattice shows specific symmetry, the easy axis will normally reflect this symmetry. However, if the lattice has many deformities, there may not be any major global symmetry, and the spontaneous magnetization will be weakened or randomized.

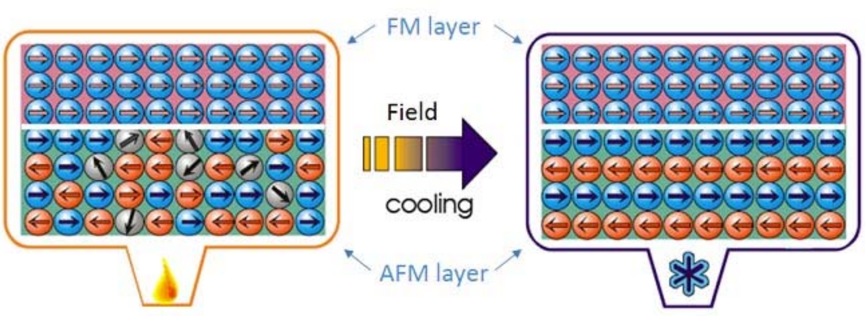

Fig. 2: After magnetic thermal annealing, an antiferromagnet becomes much more ordered and pins the adjacent ferromagnetic layer

If a deformed FM lattice is annealed at a high temperature, the spins of each individual atom will align with the externally applied field. When maintained at a high

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temperature, this spin-field interaction will begin to reorganize the lattice somewhat, due to the spin-orbit interaction (SO), or the interaction between the atomic orbitals and the electron spins inside a crystal lattice. Eventually, the system will attain equilibrium within this field, causing a lattice reorientation such that the easy axis becomes parallel to the applied field. When the temperature is reduced, then, the lattice becomes "locked or frozen" once again, and the magnet attains a new magnetization direction with a much robust and more well-defined easy axis.

Not only can magnetic thermal annealing reorient the easy axis and remove lattice defects, it can also change the shape of the object. For example, if a thin film has nonuniform thickness, the magnetic field will reflect this asymmetry. This poses a problem for magnetic thin-film applications that require a very consistent material. Thermal annealing can help the film achieve structural equilibrium, removing shape deformities as well as structural ones.

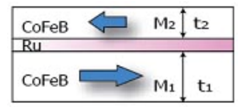

Fig. 3: A synthetic antiferromagnet

Setting up Exchange Bias in Ferromagnetic/Antiferromagnetic Multilayers

One important application that magnetic annealing is used for is creating exchange bias in a magnetic thin film. Exchange bias causes a shift in the hysteresis loop of a FM film, as shown in Figure 1. This shift causes the "pinning" effect in a magnetic tunneling junction (MTJ) or a spin-valve based on giant magnetoresistance effect (GMR). The establishment of exchange bias allows one FM layer in a junction to respond to an external field while keeping the other's magnetization intact. This is the basic mechanism behind a spin-valve, and it is an invaluable technique for creating MTJs and read-write heads in hard disk drives.

Exchange bias works by placing an AFM (figure 2) directly adjacent to a FM layer. When annealed in an external field, the FM layer has its easy axis set parallel to the field direction. As the bilayer is cooled to below the magnetic ordering temperature call Neel temperature of an AFM, the spin structure in the AFM aligns itself to the ferromagnet such that the topmost layer of spin is parallel to the FM's magnetization. Since it must adopt the configuration in figure 2, the AFM's symmetry axis becomes parallel to the FM's easy axis. The effect of the AFM/FM junction is an effective pinning of the FM magnetization parallel to the topmost layer of the AFM, giving rise to the exchange bias phenomenon. At room temperature, the topmost layer of the AFM exerts an internal effective magnetic field (also called molecular field). This internal field is called exchange biasing field and is responsible for the exchange biasing phenomena.

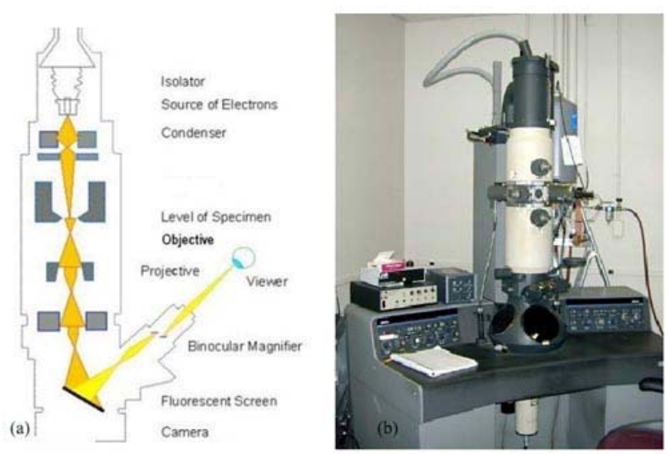

Fig. 4: Schematic drawing of a transmission electron microscope (a) and a photograph of a Phillips 420 TEM

Setting up Synthetic Antiferromagnetic Coupling

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The simplest way to create exchange bias is by having an AFM adjacent to the layer to be pinned. However, using a synthetic antiferromagnet (SAF) is another method that causes a stronger pinning as well. SAF has the advantage of reducing stray magnetic field effect due to magnetic poles at the edges of ferromagnetic thin films.

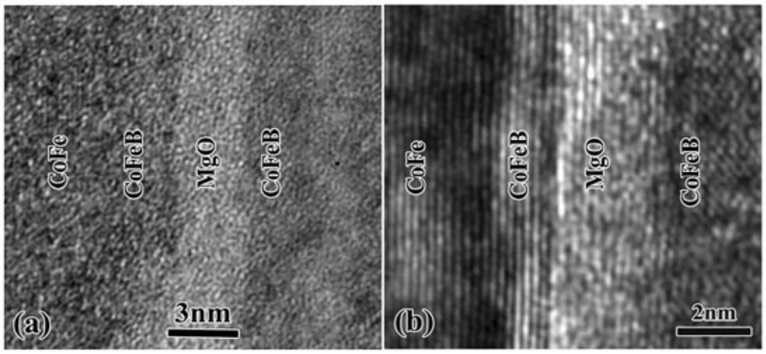

Fig. 5: Cross sectional images of a magnetic tunneling junction. Materials after annealing (b) are much less disordered structurally than before annealing (a).

The SAF works similar in principle to the AFM. The structure is a trilayer consisting of two FM layers separated by a nonmagnetic metallic layer. The FM layers are anti-aligned due to electron coupling through the metallic layer. In order to anti-align the two FM layers in a SAF, both layers need to be annealed in a high magnetic field, aligning their easy axes parallel to each other. Since one layer has slightly different anisotropy, it will flip direction once the field has been removed.

Magnetic thermal annealing significantly improves magnetic structures inside SAF films. The antiparallelly aligned FM films will not generate external magnetic fields because their opposite poles are very close to each other. Also in SAF, both FM layers are in the single domain state, which will enhance magnetic performance in various magnetic devices.

Enhancing Giant Magnetoresistance in Magnetic Devices

In modern processing of MTJ and GMR magnetic devices, magnetic thermal annealing will increase the magnetoresistance substantially (Figure 7). During thin film deposition, the crystalline and magnetic structures of the thin film devices may possess high degrees of disorder. Post deposition thermal magnetic annealing can remove these disorders, and yield the optimal magnetic performance of the devices. Often, with proper magnetic annealing processes, the magnetoresistance of an MTJ or GMR device can see its magnetoresistance increase by more than a factor of ten.

Fig. 6: Micro Magnetics' SpinTherm-1000 High Vacuum Magnetic Thermal Annealing System

Magnetic Thermal Annealing Systems

A magnetic thermal annealing system comes with different specifications tailored to specific applications. The system must provide a high vacuum environment for the samples to be annealed. Any oxidation of the samples may damage the crystal and magnetic structures of the thin films, as well as cause adverse effects on magnetoresistance or other magnetic properties.

The system must also be equipped with a magnet that can generate a large and uniform magnetic field within the sample area. Sometimes the

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area may be large, like a stack of many Silicon wafers. The magnetic field must be uniform over the whole space, and it must be large enough to perfectly align the magnetization vectors of the samples in one direction.

Additionally, the system should establish a uniform temperature over the whole sample area. Spatial variation of the annealing temperature will create inhomogeneous magnetic properties throughout the samples. The temperature must be controlled (ramping up, maintaining, and cooling down) by a computer or a processor accurately and easily. Various thermal annealing recipes should be able to be stored in the software.

Finally, the high temperature furnace must be well insulated from the magnet. Otherwise, magnet heating will damage or shorten the lifetime of the magnet system.

Micro Magnetics' SpinTherm-1000 High Vacuum Magnetic Thermal Annealing System is a system that satisfies all the requirements above. The SpinTherm-1000 is used to enhance performance of spintronic devices, magnetic materials and components. It is a fully automated thermal annealing station with unlimited user defined recipes. Magnetic components in multiple shapes and forms can be thermally treated or annealed in temperatures up to 700 degrees C and in strong a magnetic field up to 4 kiloGauss, all in a high vacuum environment or in a special gas with a selected pressure.

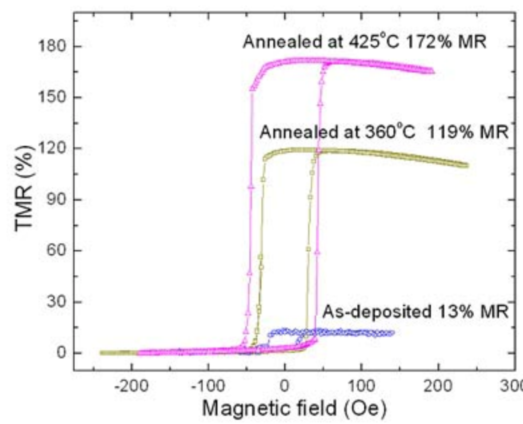

Fig. 7: Magnetic thermal annealing can reorient and strengthen the easy axis of a magnetic thin film, allowing for much higher magnetization in a magnetic field

To see a brochure for the SpinTerm-1000, click here. Please call Micro Magnetics to discuss your need of magnetic thermal annealing.

Keywords: magnetic thermal annealing, magnetic annealer, magnetic annealing, spintronics, spin electronics, spin based electronics, magnetoelectronics, magnetic disorder, GMR, MTJ, spin valves, exchange biasing, ferromagnet, antiferromagnet, synthetic antiferromagnetic coupling, information storage, MRAM, magnetic pinning, ferromagnetic coupling, antiferromagnetic coupling, Neel temperature, magnetic easy axis, magnetic domain, magnetic anisotropy, shape anisotropy, magnetocrystalline anisotropy, magnetic relaxation.