# 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.

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.

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 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.

# 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 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.