Technical Paper

Magnet Designs for Magneto-electronic Thin Film Processing

March 2003

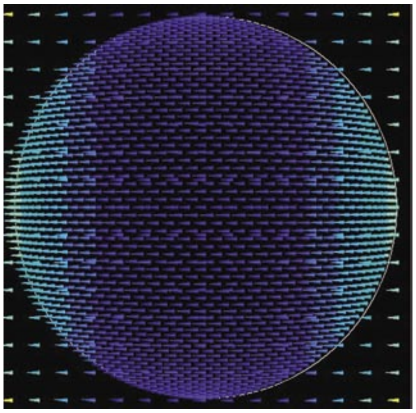
Mike Schilling and Chris Ras

Introduction

Magnetic fields are pivotal in the manufacture and processing of advanced magneto-electronic thin films. These include giant magnetoresistive (GMR), current perpendicular to plane (CPP) spin valves and magnetic tunnel junctions (MTJ) thin films.The magneto-electronic films are utilized in: disk drive read/write heads, magnetic sensors and MRAM devices.

A magnetron delivers a field that enables fast and efficient deposition of permalloy and other materials onto silicon or ceramic substrates. During the deposition process of some magnetic materials, a permanent or an electromagnetic biasing assembly orients the film. After deposition, some films are pinned by annealing the wafer in a magnetic field to induce an easy axis of magnetization (Fig. 1). A magnetizing field is initially required to establish a single domain in the MR strip that is supported by patterned longitudinal bias films. Finally, in MR heads a magnetizing field is necessary for the reduction of Barkhausen noise in the MR signal. Each of these processes utilizes a magnetic field with specific performance characteristics. Magnet designs that produce these fields are in a state of constant refinement.

Figure 1 | Annealing Field



Magnet Design Considerations

The following parameters need to be considered when designing and selecting the proper magnet design for the process.

Field

- Field Magnitude
- Field Magnitude Uniformity
- Volume of Uniformity
- Dispersion Angle
- Skew Angle
- Fixed Field or Variable Field Source
- Surrounding Components
- Stray Field

Environment

- Temperature
- Vacuum
- Gases or Liquids
- ESD Requirements

Mechanical

- Space and Weight Requirements
- Structural Design
- Encapsulation

Field Source

- Permanent Magnet
- Electromagnet
- Super-conducting Magnet

Magnetron Sputtering of Magnetic Materials

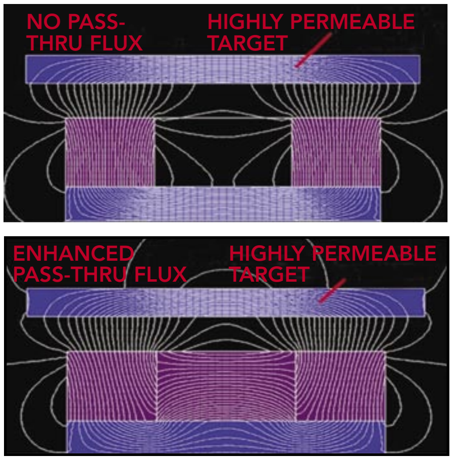
Magnetron sputtering is the dominant thin film process because of its high deposition rate. In sputtering, the material to be deposited is called the target, and the object to be coated is called the substrate. Sputtering occurs in a plasma, where ionized gas atoms are electrically accelerated to bombard the surface of the target, causing atoms to be ejected toward the substrate. A magnetron, usually consisting of permanent magnets, delivers a magnetic field that traps electrons near the target and dramatically increases the ionization of gas atoms. A minimum field of 200 Oe (15.9 kA/m) is required for most magnetron sputtering situations. It is difficult to develop this field strength when sputtering magnetic materials, such as permalloy, because the target shunts the magnetron field and prevents most flux from reaching the surface. To overcome this, a magnetron must produce enough field to magnetically saturate the target and provide additional penetration flux for sputtering. To accomplish this, magnetron designers can switch from traditional Alnico or ceramic magnet material to newer high-energy Sm-Co or Nd-Fe-B materials.

To further increase the penetration flux, a patented high flux design *(1)* uses an additional magnet between salient pole magnets. *(See Figure 2)*

Figure 2 shows the flux lines generated by a conventional magnetron arrangement compared to a high flux arrangement. Note in the conventional design, significant flux is lost through the keeper on which the magnets rest and never passes above the magnets. By filling the gap between poles with magnet material, flux is forced above the magnets and through the magnetic target. Another way of interpreting the flux line plots is with the principle of superposition, the net magnetic field is the sum of fields generated by each component magnet. Adding a bar magnet between the two pole magnets is the most logical means of increasing flux near the target.

Figure 3 is a plot of the flux density at a given height above the magnets for a conventional design and a high field design. The high flux design delivers a stronger field than the conventional design. The amount of improvement over an existing magnetron varies with geometry. The significance to someone sputtering a magnetic material is the ability to sputter in systems requiring deeper penetration and pass-through flux. A thicker target may also be used, which increases throughput and decreases the number of target changes that result in exposure of the system to atmosphere. In addition, the target can now be placed further away from the magnetron, offering some flexibility in system geometry. *(See Figure 3)*

Figure 2 | Conventional vs. High Flux Magnetron



Thin Film Biasing

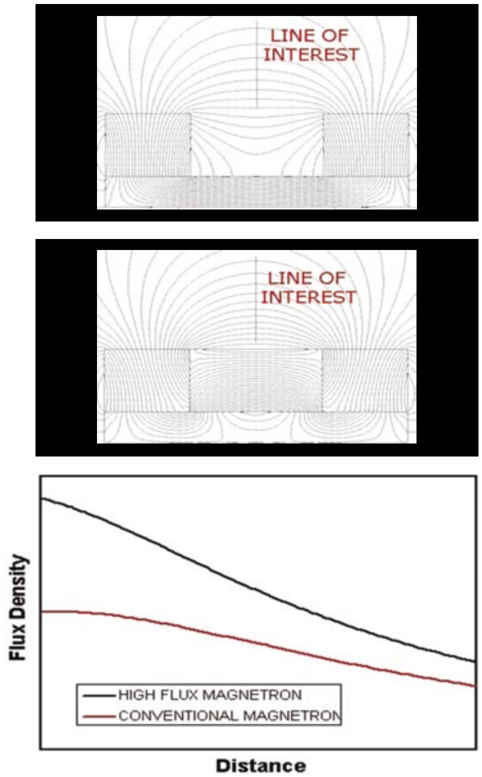
Sputtering within a magnetic bias field can enhance the magnetic anisotropy of thin-film magnetics. Magnetic biasing can be achieved by locating the substrate within an alignment field that is generated by either electromagnets or permanent magnets (Fig. 4 and 5). Permanent magnets provide a fixed field and electromagnets can provide adjustable, bipolar or rotational fields. The space available and the location of the bias frame relative to substrate usually limit the field magnitude and uniformity. Orthogonal anisotropy can be produced with switching electromagnets *(2)* or rotating permanent magnets. *(See Figure 4 and 5)*

Uniform Field Annealing Dipole

The difference between as-deposited and annealed material is dramatic. Magneto-electronic films are frequently annealed within a magnetic field to enhance exchange biasing and improve the MR% ratio. Requirements of the magnetic field are that the flux lines be straight and parallel, and the field strength be uniform over as great a volume as possible to maximize throughput. Such a field can be produced by either a permanent magnet, an electromagnet or a super-conducting magnet arranged in a dipole configuration. Electromagnets and superconducting magnets allow for field variation. Permanent magnets produce fixed fields, are more compact, and require no energy input or provisions for cooling.

For lower field requirements, 0.2 to 2.5 kOe (15.9 to 200 kA/m), the most common permanent, or electromagnet, dipole configuration is a C-shaped steel yoke with magnets, or coils, located nearest the gap. This minimizes flux leakage from the pole faces, and offers good accessibility to the gap. Although a simple C-shaped geometry produces straight and uniform fields, its volumetric efficiency is limited by this geometry's inherent fringing and leakage fields. Various techniques can be employed to minimize these effects.

Figure 3 | Relative Comparison of Flux Density vs. Distance



For higher field requirements 5 to 10 kOe (400 to 800 kA/m) the permanent magnet dipole is perhaps a better approach (Fig. 6). Permanent magnet dipoles require no power and have a smaller footprint. Electromagnets can require hundreds of kilowatts of power, and cooling facilities. Two permanent magnet approaches are commonly used, a Halbach dipole or a Stelter dipole *(3)*.

Halbach dipoles are an excellent choice for larger volumes and multiple wafers. Halbach dipoles utilize a plurality of permanent magnets arranged about a longitudinal axis within a cylindrical yoke. This inherently efficient design creates a uniform magnetic volume within the cylinder bore. The resultant diametric field is applied across the wafer stack. *(See Figure 6)*

For limited volumes and fewer wafers, the Stelter design is the more efficient. The Stelter design utilizes a plurality of magnets arranged and oriented both parallel and in quadrature relative to the axis of the uniform, cylindrical volume.

For production of large wafers where fields greater than 15 kOe (1,200 kA/m) are required, super-conducting magnets are the preferred option.

Magnetizers for Exchange Biased Heads

All magnetic materials are initially comprised of randomly oriented domains. The magnetization process rotates domains into common alignment and causes those aligned with the magnetizing field to grow in size. Full saturation would result in a single aligned domain if all anisotropy mechanisms can be overcome.

Practical magnetic materials have an internal self-demagnetizing field, which creates unfavorable orientations in magnetic domains near geometric extremities. Shorter magnets have a greater self-demagnetizing field (hence more unfavorably oriented domains) than longer ones. A high self-demagnetizin field effectively resets a material to its small domain, initial magnetization condition where Barkhausen response exhibits itself as noise. Step function domain alignment and growthcause Barkhausen noise in the initial magnetization phase. *(See Figure 7 and 8)*

MR sensors tend to be short in order to reduce track width and maximize areal density. This physical limitation typically results in units that have a high self-demagnetizing field and are subject to Barkhausen noise. To overcome this, an exchange bias film is deposited at the ends of the permalloy

Figure 4 | Adjustable Electromagnet

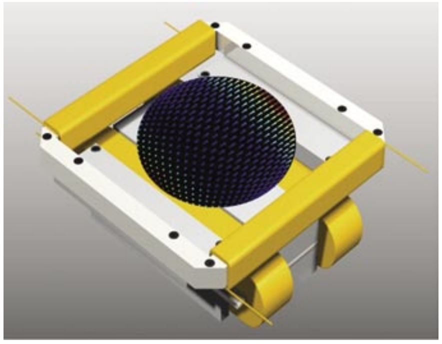


Figure 5 | Fixed Permanent Magnet

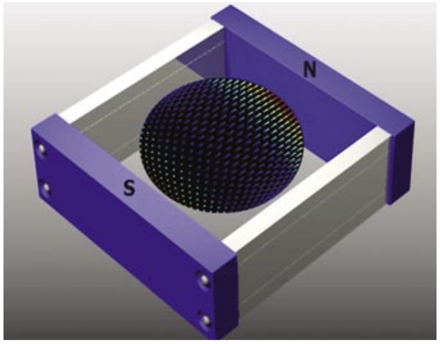


Figure 6 | 1 T Permanent Magnet and Vacuum Furnace Chamber

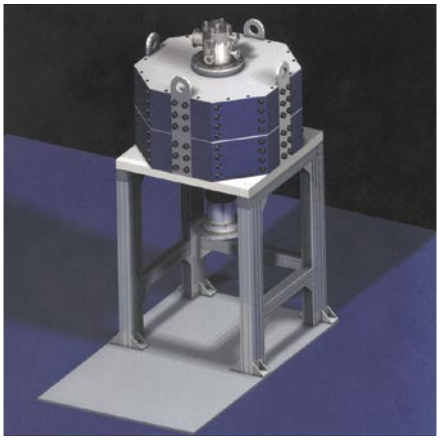


Figure 7 | Electromagnet

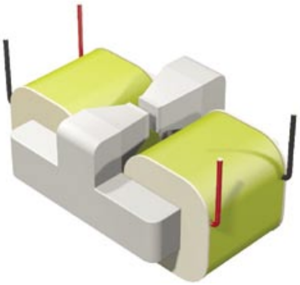
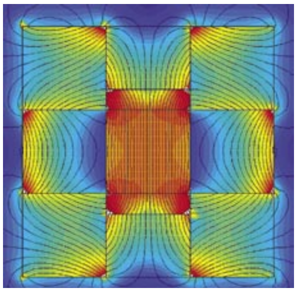


Figure 8 | Permanent Magnet



strip. Exchange coupling between the two films overcomes the selfdemagnetizing field of the sensing element, and supports a near single domain structure. Operating in this biased condition eliminates Barkhausen noise and maximizes magnetic response to signal inputs.

To develop the biasing field, the MR element must be initialized. The initializing field can come from an electromagnet (Fig. 7) or permanent magnet with inherent advantages and disadvantages for each. An electromagnetic field can be switched on and off, but power supplies and cooling can add to clean room costs. Permanent magnet assemblies can provide the required field intensities and uniformity, but they cannot be switched off, and initial cost is usually higher.

A high magnetic field for initialization can be developed with a patented permanent magnet assembly *(4)*. Figure 8 shows the magnetic flux lines through the cross section of the magnet arrangement. Colors of the spectrum indicate flux density, with red being the most intense. Flux in the center gap travels in the vertical direction. Using rare earth magnets, this design is capable of generating gap flux densities as high as 30+ kOe (2.4 MA/m) this field is greater than the residual induction of the magnet material. This is accomplished by superposition of magnetic fields in a fashion similar to the previously mentioned magnetron design. While fields of that magnitude are not required for MR head processing, this magnet arrangement is needed when the working gap is large. Other desirable features of this design are inherent flux straightness and uniform flux density in the gap, which are by-products of flux focusing. These features ensure tight control in magnetizing parameters.

Summary

In the manufacture of magneto-electronic films, engineered magnetic fields are required in several important steps. Magnetic fields possess a simple elegance in that they follow a few simple rules. With knowledge of these rules and computer analysis software, one can constantly refine a magnetic field to enhance desired characteristics such as field strength, field straightness, and field strength uniformity. Existing manufacturing processes such as sputtering, annealing and head magnetizing will continue to be improved with new magnet designs. Future magnet applications in the recording industry will certainly be subject to the same optimization.

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If you have any enquiries regarding the content of this article, please contact:

Mike Schilling, Business Manager
Dexter Magnetic Technologies
1050 Morse Avenue
Elk Grove Village, IL 60007
USA
Tel | 800-317-2537 ext. 3018
Fax | 800-345-8193
mschilling@dextermag.com
www.dextermag.com

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