The Design of Rotating Magnet Sputter Sources

ABSTRACT

Thin films - sometimes only fifty to one hundred layers of atoms - play a central role in the fabrication of hard drive memory disks. The required films (typically chromium, magnetic alloy and carbon) are usually deposited by sputtering, where the target material is bombarded by energetic argon ions in a low-pressure plasma discharge, to expel free atoms at the target material.

The Design of Rotating Magnet Sputter Sources

Robert J. Kolenkow, *Intevac VSD, Santa Clara, CA, USA*
Craig Armstrong, *Integrated Engineering Software, Winnipeg, MB, Canada*

Abstract

Thin films – sometimes only fifty to one hundred layers of atoms – play a central role in the fabrication of hard drive memory disks. The required films (typically chromium, magnetic alloy, and carbon) are usually deposited by sputtering, where the target material is bombarded by energetic argon ions in a low-pressure plasma discharge, to expel free atoms of the target material.

Proper design of sputter sources is central to obtaining desirable performance features such as highly uniform film thickness, full surface target erosion, and long target life (i.e. many disks coated per target). Recent advances in design methods, including three-dimensional electromagnetic simulation software, are resulting in new sources of substantially higher performance than those based on earlier semi-empirical approaches.

Introduction

Modern sputtering equipment uses magnetron sources, where an artfully arranged magnetic field strongly confines the plasma electrons to move in tight cycloidal paths. This decreases electron leakage from the plasma, so that each electron produces many ions, making the rate of sputtering practical for production.

Early magnetron sources for disk coating typically used a cylindrical coil to produce the magnetic field. This arrangement is easy to design without much calculation, but its circular plasma track erodes the target only in a localized narrow groove. Because the target has to be discarded when the maximum erosion depth approaches the initial target thickness, these early sources had short target life and forced the customer to shut down the coating equipment for frequent target changes, with costly impact on labour requirements and on production.

Rotating Magnet Sources

The simple ring geometry in a circular magnetron allows little freedom for tailoring performance. For instance, if the substrate is moved closer to the target, the deposition rate increases but the film thickness uniformity tends to decrease. Even at the optimum spacing, the film thickness uniformity with practical circular magnetrons is no better than ±5% or so.

Circular magnetrons also leave large areas of the target unsputtered, leading to the build-up of backscattered redeposition that promotes arcing and consequent particulate generation. Full surface target erosion is desirable, because it beneficially keeps the target surface clean.

Rotating magnet magnetron sources with non-circular plasma tracks overcome many of these difficulties, and have largely replaced circular magnetrons in disk coaters. In a rotating magnet source, an array of permanent magnets behind the target produces a closed-loop plasma track at the target surface. (All practical plasma tracks must be closed to allow continuous circulation of electrons.) Figure 1 shows the instantaneous plasma track from a rotating magnet source, as seen through a vacuum chamber viewport.

By rotating the magnet array on the axis of the target, the plasma track is swept cyclically across the target to give a cylindrically symmetric target erosion typically much broader than from a circular magnetron, substantially increasing target life and also allowing for the possibility of full surface erosion. The rotation speed may be as high as 600 rpm, which is fast enough to give many rotations during a typical 3 or 4 s deposition process; film quality was not found to change in tests from 100 rpm to 600 rpm. The time scale of collision processes in the plasma is orders of magnitude faster than the rotation speed, so that at any instant the plasma track is effectively static as far as sputtering is concerned.

Figure 2 shows a production rotating magnet array or "pole" designed for coating 95 mm hard disks. It produces full surface erosion, as demonstrated by the partly eroded chromium target in Figure 3.

Rotating Magnet Source Design

Performance requirements and track shape

For most hard disk coating applications on 95 mm disks, the principal source design issues to be resolved are

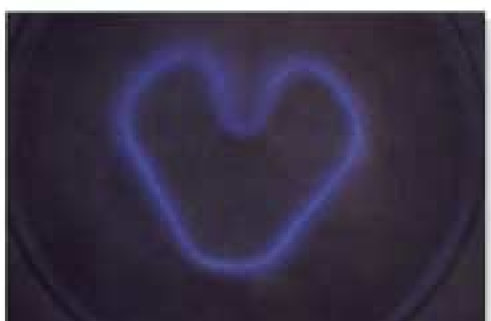


Figure 1
A magnetically confined glow discharge plasma track loop generated by an experimental rotating magnet pole. The deep cusp is characteristic of tracks that give full surface erosion, because the plasma track must pass at least in part over the centre of rotation.

- Excellent film thickness uniformity, typically down to ±2% (3 sigma) at the given source-substrate distance and for the given target diameter
- High target inventory, typically 15-20 MÅ or greater from a 150 mm diameter target. (Inventory, a useful measure of target life, is the total coating thickness deposited on substrates from a target during its useful life. By convention, the target is assumed to have an initial thickness of 6.35 mm, and to require replacement when the maximum erosion is 90% through.)
- Full surface erosion
- Controlled film thickness rolloff at the substrate i.d. or o.d.

All of these qualities are determined by the detailed shape of the plasma track at the target surface. The track shape, in turn, is generated by the arrangement of magnets in the array.

Several factors militate against using trial-and-error methods for developing an acceptable track shape. First, the performance depends sensitively on the detailed track shape [1, 2]. Secondly, deposition at a given radius on the substrate depends upon large regions of the track, and this global behaviour makes it very difficult to define a convergent procedure for improving the performance of an initial track using measured thickness profiles. Nevertheless, fairly acceptable rotating magnet sources have been designed by semi-empirical methods [3] (±5% uniformity over a 200 mm wafer, 3 sigma, and with full surface erosion; inventory not quoted).

Experience with potted magnet assemblies has shown that despite the sensitivity of performance to track shape, a desired track shape can be held closely over the unit's life and from unit to unit, making rotating magnet sources practical for production.

EROSION PROFILE

The erosion profile of a partly eroded target is measured experimentally by the depth of material lost as a function of radial position across the target. The significance of the erosion profile is its proportionality to the rate of sputter emission: the depth lost at a given radius is the time-integrated emission rate (usually assumed constant) at that radius.

Workers in sputter deposition have long recognized that the performance of a source, in particular the thickness deposition profile on any substrate at any source-substrate distance, can be inferred from the erosion profile using an inverse-square law [2, 4, 5]. The accuracy is usually quite good, even with modest assumptions. A variety of secondary corrections can be applied if necessary, such as detailed knowledge of the angular dependence of the emitted atoms and the effects of gas scattering as the sputtered atoms travel between the target and the substrate.

It has recently been realised [6] that it is possible to invert by numerical approximation the Fredholm integral equation of the first kind that expresses thickness profile in terms of erosion profile, to derive an erosion profile that will give a desired thickness profile ("constant" thickness is usually desired). A practical approach is to express the erosion profile as a Chebyshev series with coefficients to be determined. The coefficients can then be found by optimization, which is a stable method for solving such ill-posed problems [7].

Optimization proceeds iteratively, and as it proceeds the thickness uniformity improves and the inventory decreases. The source designer stops the procedure when the predicted performance meets the stated requirements; if the stated requirements are never met, the designer can start again with different assumptions concerning target size or source-substrate distance.

Another advantage of optimization techniques is that the calculated erosion profile is close to an optimum erosion profile. The designer need not bother to look for another profile that might have substantially higher performance. Figure 4 shows normalized erosion profiles suitable for coating 95 mm disks at a source-substrate distance of 35 mm, with predicted thickness uniformities of ±4% (16 MÅ inventory) and ±2.5% (14 MÅ inventory). Uniform erosion would give maximum inventory, but is undesirable here because it does not give good thickness uniformity.

An important feature of this design method is that the optimized erosion is specific for the substrate size, for the target size, and for the given source-substrate distance; with earlier methods, it was not possible to design for a definite geometry. The maximum erosion radius, which is input to the original problem statement, must be suitably less than the target o.d., to prevent excessive electron loss. Conversely, the designer can be assured of finding the smallest possible target for a given performance.

The capability of specifying the source-substrate distance is valuable in practical source design. A reasonably close spacing is desirable, because it raises the deposition rate; the design method allows the designer to see if the performance specification can be met at the chosen spacing.

EROSION PROFILE AND TRACK SHAPE

Once a suitable erosion profile has been found, the next step is to design a track that will yield the profile. At the present time, the approach to track design is largely trial-and-error, using the principle illustrated in Figure 5. The process converges (possibly not uniformly), because at each stage the erosion profile predicted from the assumed track shape can be compared to the optimized profile, and reshaping can be applied to discrepant radial regions.

As a first-order correction to the track's finite width, it can be assumed to have a Gaussian cross-section. The track at small radii must be routed so that its outer limb just brushes the centre of rotation, to give full surface erosion without the erosion being so excessive as to limit target life.

Figure 2
A rotating magnet pole. The magnet bars are potted in place in a casing. The casing design is generated from a computer file that specifies the coordinates of the magnets

Figure 3
A partly eroded 6.35 mm magnetic alloy target and a deeply eroded 12.7 mm chromium target. Both targets exhibit full surface erosion; the high target utilisation possible with a rotating magnet source is especially evident in the chromium target

Researchers at Varian Associates, e.g. [1, 2, 8], developed a widely used "heart-shaped" rotating magnet source based on their parametric equation in polar coordinates for track shape. Their equation expresses the polar angle of a point on the track as a function of radial distance to the point, in terms of an integral involving certain preselected erosion profiles. By its mathematical nature, this equation fails for many usable erosion profiles. It is further limited by describing only single-valued tracks that always spiral outward. The equation does not hold at small radii, and empirical methods are needed to secure full surface erosion.

In contrast, the design method [6] has generated tracks of great generality that may spiral inward as well as outward (or remain sensibly constant over a region), and that may be multiple-valued (two or more values of radial distance for a particular polar angle). This great generality gives the designer a wider repertoire and more design freedom.

TRACK SHAPE AND MAGNET ARRAY

The final design task is to devise a magnet array that will generate the track. According to the principles of electron confinement in magnetrons, the centre of the track follows the locus where the field component perpendicular to the target equals zero ($B_z = 0$).

The design begins by laying out an approximate array of magnet bars, typically chosen to be neodymium-iron-boron (NdFeB) for their high energy product. A good start is to assume that the centres of the magnets lie on the desired locus. Using commercially available 3-D boundary element software [9], the B-H characteristic of the magnets (second quadrant) is entered using available input commands. The fields are then calculated at the height of the target surface and the locus $Bz = 0$ is traced out using the built-in contour plotting. Comparison with the optimal track suggests how the magnet bars should be moved to give closer agreement.

Such modelling clearly shows that the locus tends to be pushed out beyond the magnet centres; earlier designers, lacking such calculational tools, were puzzled that the measured locus did not coincide with the centreline of the magnets [2].

A few iterations are usually sufficient to complete the array design, although deep cusps in the track require trials of various configurations. These problems can be fairly large, up to 4000 elements and 12 000 unknowns; Figure 6 shows the layout of one-half of an array, with boundary element patches. The code runs fast enough to make it practical to test a number of magnet configurations when designing complex convoluted tracks.

Figure 7 compares the measured track locus [10] for a production pole with the predicted track. The agreement is clearly excellent, removing any uncertainty in this aspect of source design.

The symmetry features of the code require only half of the array to be calculated. A more subtle aspect of symmetry comes about because the sources in a disk coater are installed in facing pairs so that both sides of the hard disk substrate can be coated at once. The poles are so powerful that each source produces significant fields at the opposing target, affecting the shape of the plasma track, especially at small radii. Using symmetry, this effect can be taken into account without increasing computation time. It is important for performance, because in some pole designs one source alone does not produce full surface erosion; the presence of the opposing source is necessary.

The strength of the transverse magnetic field at the plasma track is also an important factor in source design. The minimum field along the track should be high, preferably greater than 500 G, to allow relatively thick targets or targets of high permeability to be stably

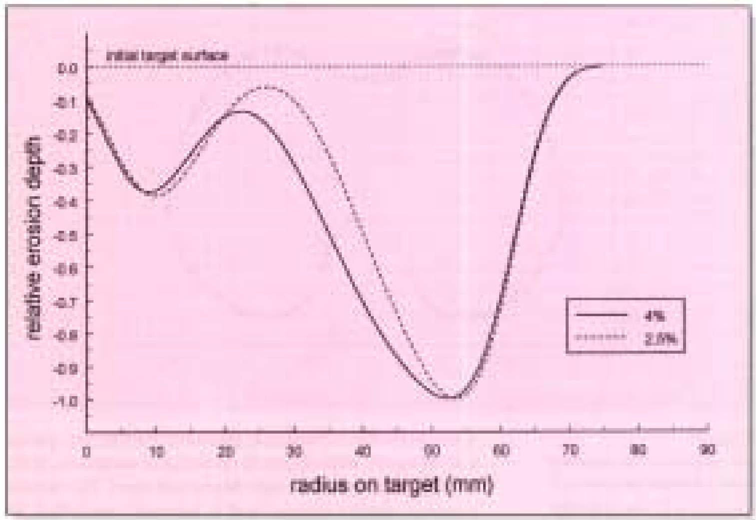


Figure 4
Two optimized erosion profiles designed for operation at a source-to-substrate distance of 35 mm. One profile is predicted to give ±4% thickness uniformity, and the other ±2.5%. The profile with the better uniformity has less inventory

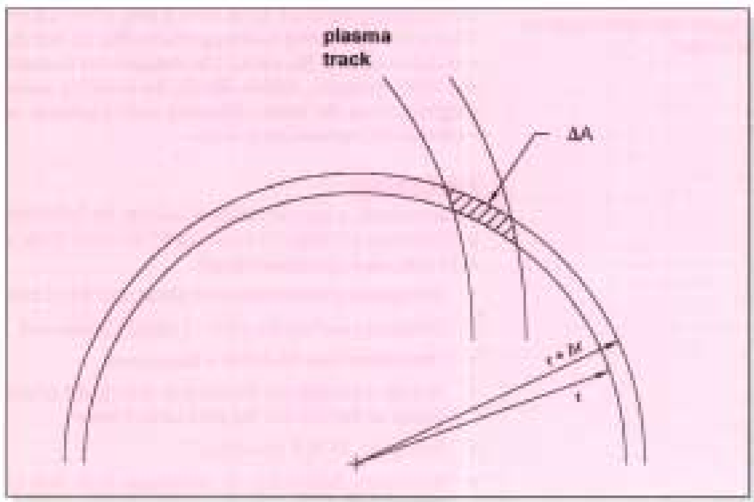


Figure 5
Principle of rotating magnet track design to generate a desired erosion profile. The relative plasma erosion from r to r + Δr is proportional to the area of intersection ΔA relative to the total area of the band 2πrΔr. To make the erosion at r as small as possible, the plasma track should cross the band radially; for substantial erosion, the track should skim tangentially along the band for a long distance

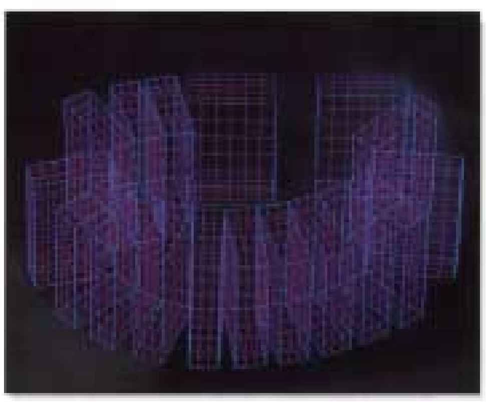


Figure 6
A screen from the 3-D magnetic field solver. The magnet bars from one-half of a pole array are shown. The surfaces carry rectangular patches for application of the boundary element calculational method

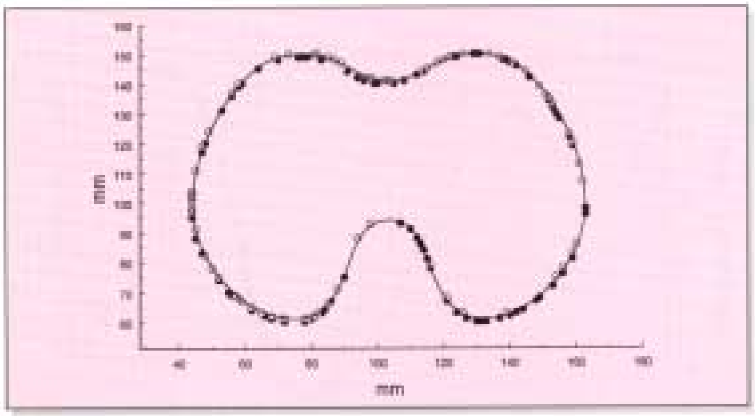


Figure 7
Comparison of the measured and calculated plasma track locus $B_z = 0$. The open and closed circles are measured points on the locus, for two different poles of the same type, as extracted from magnet scanning data. The solid line is the locus calculated by the 3-D magnetic field solver; agreement is excellent

sputtered at low to moderate pressures. Further, the sputter rate along the track depends on the local transverse field, so high fields promote high deposition rates. The dependence of sputter rate on field is not easily modelled, so if the maximum field is substantially higher than the minimum field, the resulting erosion profile will differ from the desired optimal profile, and the source performance will not be as predicted assuming a constant rate.

The transverse field at the track is readily predicted by overlaying the track locus onto a map of the calculated contours of total field magnitude. (Recall that $B_z = 0$ at the centre of the track.) The designer can increase the field strength, within limits, by packing more magnets along the track, adjusting their positions to maintain the optimal track locus.

PERFORMANCE

As an example, a recently designed pole has the following performance for deposition onto a 95 mm disk from a 6.35 mm thick chromium target:

- Operates at a source-substrate distance of 24-27 mm
- Thickness uniformity ±2% (3 sigma) [measured
- Deposition rate 88 Å/kW-s [measured
- Rolloff at the disk o.d. for the pole close to the target, rollup at the o.d. for the pole farther away
- Inventory 23 MÅ [predicted
- Maximum field 1200 G, minimum field 800 G [calculated

In contrast, a circular magnetron source would need to operate at 50 mm, giving a uniformity of ±5% (3 sigma), a deposition rate of 45 Å/kW-s for chromium, and an inventory of approximately 8 MÅ. With a circular magnetron, the depositions take longer, target life is shorter, and the film is less uniform.

REFERENCES

[1] R. L. Anderson and J. C. Helmer, "Sputtering Apparatus with a Rotating Magnet Array Having a Geometry for Specified Target Erosion Profile", US Patent No. 4,995,958 (1991).

[2] D. J. Harra, "Sputtering Apparatus with a Magnet Array Having a Geometry for a Specified Target Erosion Profile", US Patent No. 5,314,597 (1994).

[3] P. H. Ballentine, D. Heimanson, and A. T. Stephens II, "Apple-Shaped Magnetron for Sputtering System", US Patent No. 5,248,402 (1993).

[4] S. Swann, Vacuum, 38, 8-10 (1988) 791.

[5] Q. Fan, X. Chen, and Y. Zhang, Vacuum, 46, 3 (1995) 229.

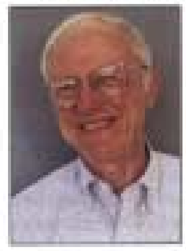
[6] R. J. Kolenkow, "Methods and Apparatus for Sputtering with Rotating Magnet Sputter Sources", US Patent No. 5,850,327 (1998).

[7] L. M. Delves and J. L. Mohamed, "Computational Methods for Integral Equations", Cambridge U. Press, 1985.

[8] R. E. Demaray, J. C. Helmer, R. L. Anderson, Y. H. Park, R. C. Cochran, and V. E. Hoffman, "Rotating Sputtering Apparatus for Selected Erosion", US Patent No. 5,252,194 (1993).

[9] "AMPERES" from Integrated Engineering Software, Winnipeg, Manitoba, Canada.

[10] Derived from measured data taken using a Redcliffe (Brislington, Bristol, UK) MagScan magnetic field mapping system.



ABOUT THE AUTHORS

Robert J. Kolenkow received his doctorate in physics from Harvard University. He has been an industrial scientist/engineer in the equipment business for twenty years. He has been at Intevac Inc. for more than six years, specializing in instrumentation, modelling, and source design. Prior to joining industry, he was a member of the physics faculty at MIT.

Craig Armstrong is General Manager with Integrated Engineering Software Sales Inc. He has been with the company 5 years, serving in the sales and marketing department.

IF YOU HAVE ANY ENQUIRIES REGARDING THE CONTENT OF THIS ARTICLE, PLEASE CONTACT:

Daniel Gentry
Vice President, Sales & Marketing
Intevac Inc., Vacuum Systems Division
3550 Bassett Street
Santa Clara
CA 95054-2704, USA
Tel: +1 (408) 496-2270
Fax: +1 (408) 988-8145
E-mail: dgentry@intevac.com

If you have any enquires regarding the 3-D boundary element software utilized for this application please contact:

Integrated Engineering Software Sales Inc.
46-1313 Border Place
Winnipeg, Manitoba
Canada, R3H-0X4
Tel: +1 (204) 632-5636
Fax: +1 (204) 633-7780
E-mail: info@integrated.ca
Web site: www.integrated.ca