Principles and Applications of Hollow Cathode Magnetron Sputtering Sources

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ABSTRACT

Hollow cathode magnetron sources, also known as inverted magnetrons, sputter material from the inside surfaces of cylindrical targets. A substrate enclosed by the cathode will receive a high-rate coating flux simultaneously from all directions. This feature, along with their ease of scalability and adaptable geometry, makes hollow cathodes ideal for a variety of sputtering applications. Devices with high aspect ratios (length to diameter) are used for rapidly coating fibers and wires, which can be transported continuously along the axis. Larger diameter, lower aspect ratio cathodes can be used to uniformly coat other types of three dimensional objects without rotation. The enclosed geometry assures that most of the sputtered material either coats the substrate or is redeposited on the target, making very efficient use of the target material and reducing the need for chamber cleaning. And because of the magnetic field shape, greater than 90% target utilization is possible without the typical racetrack formation seen in planar magnetrons. This paper discusses the operating principles and characteristics of these devices as well as several typical applications.

INTRODUCTION

Hollow cathode sputtering sources, invented in the 1970s, are magnetrons which sputter material from the inside surfaces of cylindrical targets [1,2]. Figure 1 shows a schematic representation of such a device. Because of their enclosed geometry, hollow cathodes have been used widely since their development to coat wires and fibers. However, growing interest in functional coatings on a variety of substrates with complex geometries makes their features attractive for a wide range of coatings. We will begin with a discussion of the design of hollow cathodes, and then review their use in some specific applications and potential applications.

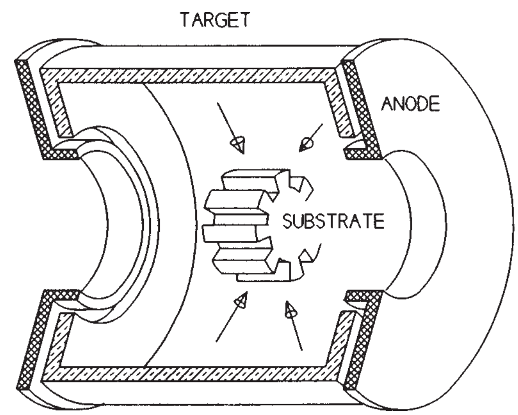

Figure 1. Schematic of a hollow cathode sputtering source.

HOLLOW CATHODE DESIGN FEATURES

Hollow cathodes use a combination of electrostatic and magnetic fields to produce an intense and very uniform plasma next to the target surface. Figure 2 illustrates the key design features. Secondary electrons emitted from the target surface are confined in the radial direction by an essentially uniform axial magnetic field. Since the electron mobility along magnetic field lines is quite high, wings, which are at the target voltage, are used to reflect the electrons back into the trap. The efficiency of this trap allows cylindrical magnetrons to operate in the low 10^{-4} Torr range [2]. The plasma density immediately in front of the wings is lower than elsewhere, and consequently they accumulate sputtered material from the target faster than they sputter [2]. This fact allows simple cylinders to be used for targets while the wings can be made of a convenient material, such as stainless steel. The high electron mobility along the magnetic field direction makes it possible to place concentric anodes at the ends of the cathode. In essence, a cylindrical "virtual anode" extends

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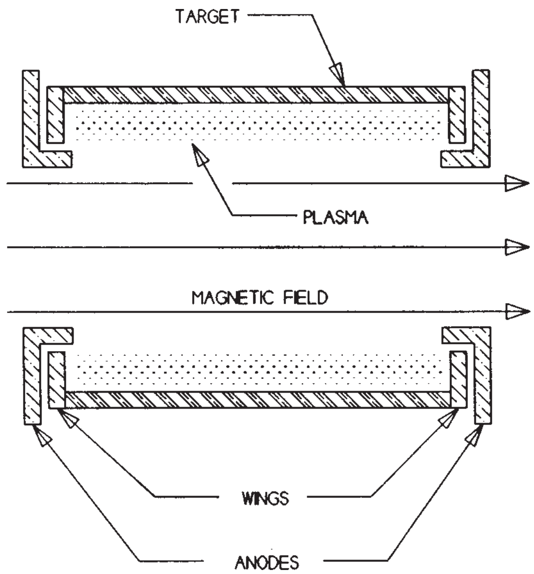

Figure 2. Key components of a hollow cathode sputtering source.

through the length of the device between the plasma and the substrate [2]. The plasma uniformity inherent in this design results in excellent target utilization. In many cases, more than 90% of the target material is consumed before replacement is needed. This fact, coupled with the ability to use simple tubes, significantly reduces target costs and equipment downtime.

The enclosed target geometry in hollow cathodes also leads to a number of important advantages. First, very efficient use is made of the sputtered material. Neglecting end effects, the importance of which depends on the aspect ratio, the sputtered material either coats the substrate or redeposits on the target. This means that a significant amount of material is available for coating, even with relatively thin-walled targets. In addition to the obvious cost and maintenance advantages this offers for any application, it also makes it possible to magnetron sputter magnetic material for reasonable lengths of time from targets that are thin enough to be saturated by the applied field.

Another interesting consequence of the cylindrical geometry of hollow cathodes is that, for materials sputtered with a cosine distribution (and neglecting end effects), the deposition rate on any surface near the cathode axis equals the target erosion rate, regardless of substrate orientation [3]. In operational terms, this becomes

$$R = 1.04\ (Ym/d)\ J,$$

where R is the rate in A/s, Y and m are the sputter yield and atomic mass of the target material, respectively, d is the film density in gm/cm^3 and J is the target current density in mA/cm^2. This means that, for many materials, all surfaces of a three-dimensional substrate can be coated simultaneously at rates of hundreds of angstroms per second.

Table 1 presents calculated rates for a number of materials of interest for functional coatings.

Table 1.

Estimated deposition rates for hollow cathodes, neglecting end effects, at a voltage of 600 V and current density of 25 mA/cm^2.

Material	Deposition Rate (A/s)
Cu	408
Al	310
Au	688
Ag	874
Ti	154
TiN	77
ZrN	100

These values are for a target voltage of 600 V and a current density of 25 mA/cm^2. The yields for compounds have been estimated by using the ratio of reactive to metal sputtering rates from the literature. End losses will reduce these rates to some extent, depending on the geometry of the cathode. For example, the measured rate in the center of a 5 cm diameter by 16 cm long target is about 70% of these values. Longer targets will produce higher rates in the center and shorter targets will produce lower rates.

As the above points illustrate, hollow cathode sputtering is capable of efficiently depositing high-rate, uniform coatings on substrates with complex shapes. The versatility, scalability and adaptability of hollow cathodes will be further discussed in the following examples.

APPLICATIONS OF HOLLOW CATHODE SPUTTERING

As mentioned in the introduction, coating wires and fibers has been one of the principal applications of hollow cathodes historically. A typical case is that of Hoshi et. al., who coated superconducting Nb_3Ge films on continuous stainless steel ribbons with a hollow cathode [4]. They used a tubular Nb target with Ge chips to form the alloy. Nb_3Sn films with good superconducting properties have also been deposited by using a Nb target with electroplated Sn strips [5]. These examples were chosen because they illustrate the ease of forming alloys from composite targets. Due to the intrinsic mixing that occurs within a hollow cathode, the use of chips, strips, or rings of various materials makes it possible to coat alloys that may be difficult to form as targets.

A wide variety of metallurgical materials has been coated with hollow cathodes, including nitrides and oxides such as TiN, ZrN, WO_3 and Cr_2O_3 [2,5]. These later compounds have been formed through reactive sputtering, which is as readily done with hollow cathodes as it is with other forms of magnetron sputtering. It is believed that the mixing discussed earlier aids in compound formation with hollow cathode reactive sputtering [5].

Metallurgical coatings are often done with the assistance of substrate bias, and the fact that the substrate is surrounded by a plasma in a hollow cathode can be an advantage for such applications [5]. Furthermore, an additional level of control is available for bias sputtering by using electromagnets to adjust the axial magnetic field. Figure 3 shows the effect of magnet current on the target voltage for a 5 cm diameter by 16 cm long Ti target operating at a power of 425 W and a pressure of 6 mTorr. The higher voltages at the low fields are associated with an increased plasma density at the substrate location.

Another advantage that results from the relatively simple geometry of hollow cathodes is the ability to scale them in size with very predictable results. There is a good discussion of this feature of cylindrical magnetrons in general in reference 2. As a further illustration, we will use the cathode shown in Figure 4. This device was designed for a target with an outside diameter of 34 cm and a length of 17 cm. It is being used to coat gold reflecting layers onto large cylindrical substrates. Figure 5 compares the calculated and measured relative thickness as a function of the axial distance from the cathode center along the centerline. In the calculations, a cosine distribution of material was assumed. Excellent agreement is seen between the expected and actual performance. Furthermore, even though this cathode has a very low aspect ratio, the axial uniformity is quite good.

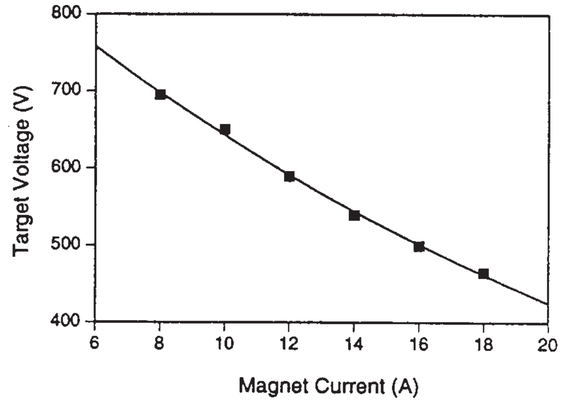

Figure 3. The effect of magnet current on the target voltage for Ti sputtering at 425 W and 6.0 mTorr.

Hollow cathode sputtering sources are well suited for the rapid cycle coating of parts. The use of very short cycle time coaters has become widespread in the audio CD industry, and we are now seeing a similar coating strategy beginning to be used in a variety of applications [6]. The high rate, uniform deposition possible with hollow cathodes and their simple, flexible geometry make them perfect for quickly coating complex objects. An example of such a device is illustrated in Figure 6. The coater consists of a central chamber incorporating a hollow cathode, which remains under vacuum at all times. On either end of the coating chamber are two load-lock chambers, separated from the coating chamber by gate valves. The cathode, coating chamber, and load locks can be sized appropriately, and can be quite small in some applications. The sequence of operations is shown in the figure.

In the first step, one set of parts is being coated while a second set is being loaded onto the fixture on the right. As soon as the parts are loaded, they are moved into the right load lock and that chamber begins pumping.

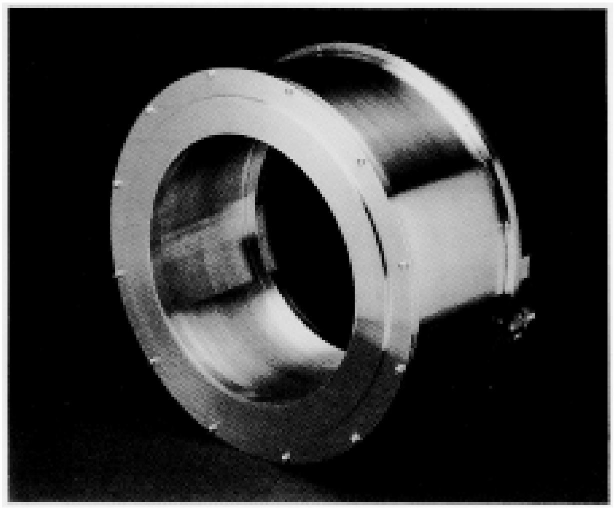

Figure 4. Cathode designed for a 34 cm diameter by 17 cm long target, showing the geometrical flexibility of hollow cathodes.

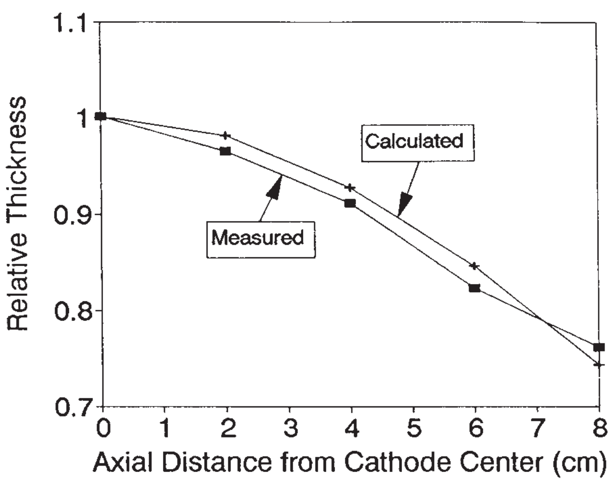

Figure 5. Agreement between calculated and measured deposition profiles for the cathode shown in figure 4.

Meanwhile, the parts that were loaded from the left can be removed from the coating chamber when the deposition is complete. When the load lock on the right reaches a sufficiently low pressure, the right gate valve can be opened and those parts can be moved into the coating chamber. When conditions stabilize, the coating of those parts can begin. Meanwhile, the parts in the left load lock can be vented to atmosphere and unloaded. This begins the cycle again. Depending on the coating material and thickness and the size of the substrate, cycle times of several seconds are possible with a coater of this design.

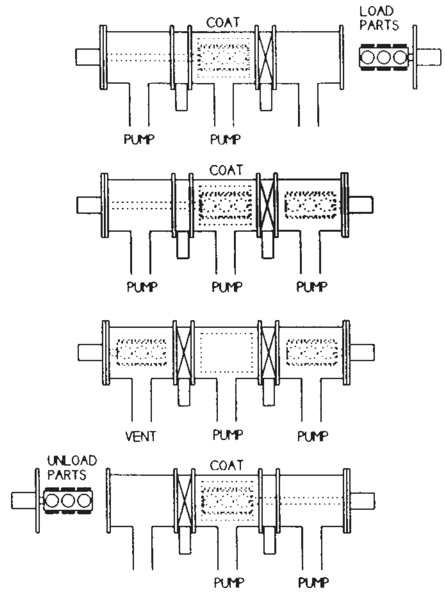

Figure 6. Operating sequence for a rapid cycle coater utilizing a hollow cathode sputtering source.

Such a device maximizes the duty cycle of the cathode and eliminates idle time while parts pump and vent. It is made possible by the symmetry of hollow cathodes and the fact that they can coat isotropically at high rates. Maintenance is reduced through the excellent target utilization and coating efficiency, and the reduced need to clean internal fixturing. The increasing demand for integrated manufacturing and continuous product flow, along with the ability to work with smaller increments of manufacturing capacity, makes coaters such as this very attractive.

SUMMARY

The design features of hollow cathode sputtering sources have been presented, which illustrate their capabilities for high-rate, uniform, efficient deposition onto three-dimensional substrates. Examples have been given to illustrate the variety of materials that have been coated with these devices. The ability to predictably scale the performance of hollow cathodes has been shown. Finally, a concept has been presented which illustrates the flexibility of these cathodes to meet the growing need for reduced cycle time coating for a wide variety of applications.

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