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Influence of the planar cylindrical target erosion zone of magnetron sputtering on the uniformity of a thin-film coating

D D Vasilev and K M Moiseev
Bauman Moscow State Technical University, 2nd Baumanskaya str., 5, 105005, Moscow, Russian Federation

E-mail: d.d.vasiliev@ya.ru, mkm430@ya.ru

Abstract. The constant change in the erosion zone of magnetron sputtering targets makes simulating their profile difficult, whilst the measurement of real-world systems requires a long working time. However, by using the measured erosion zone profile of a real target, a formula for calculating the uniformity of thin films has been developed. Using this, it has been found that the erosion zone of a 4" cylindrical magnetron target can improve coating uniformity.

1. Introduction

According to Mur's law, the complexity and size of semiconductor crystals double every year, yet the dimensions of semiconductor devices are halved. Over the last 15 years this has seen the size of the smallest unit decrease ten-fold, but with a doubling of the diameter of their substrate seven-fold increase in the dimensions of the chips in which they are used. This microminiaturization makes it far more important to create a high degree of uniformity in the layer thickness through careful monitoring of the fabrication process and imposing much stricter requirements to ensure a clean technological environment [1]. For example, a past increase in substrate diameter from 200 to 300 mm resulted in the layer uniformity changing from ±5% to ±4%, with current technology now being designed around 450 mm diameter substrates.

Of the newer microelectronic technology, single infrared photon detectors have been receiving particular attention of late, and are based on a 4.6 nm thick superconducting WSi film deposited by DC magnetron co-sputtering from separate W and Si targets at room temperature [2]. The distribution of material during magnetron sputtering, however, can lead to variation in material ratio at different points on the substrate that can cause the film to lose its superconductivity. Various forms of substrate holder rotation have been tested in a bid to alleviate this problem, but the design and experimental testing of new equipment takes enormous time and financial resources.

Computer simulation represents a way of reducing the cost outlay of improving the film uniformity of magnetron sputtering, but a key requirement of this is an ability to take into account the constantly changing shape of the magnetron target erosion area. However, registration of this erosion area is rather time-consuming due to the fact that it is unique for each magnetron sputtering source, magnetic system, target material, type of power supply, etc. The purpose of this article is therefore to provide a theoretical evaluation through mathematical modelling of the influence of erosion area on the uniformity of thin film layer produced by planar cylindrical magnetron sputtering source.

2. Physical phenomenon, underlying process

In magnetron sputtering systems for diode-type devices, sputtering occurs through bombarding a target surface with gas ions formed through an abnormal glow discharge plasma. As seen in figure 1, cavities for water cooling and magnets to confine the plasma are installed in the housing of the source, with the target of sputtering being fixed from above. The gas ions require a critical energy before sputtering can occur, with the number of atoms ejected by a single ion (the sputtering coefficient) being dependent on not just the ion's energy, but also the tilt angle and material used.

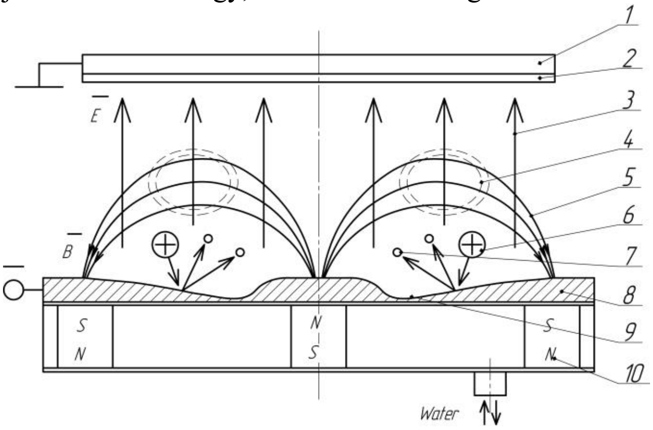

Figure 1. Schematic diagram of a magnetron sputtering system with a planar target: 1 – substrate holder; 2 – substrate; 3 – electric field; 4 – area of plasma localization; 5 – lines of magnetic force; 6 – ions; 7 – sputtering fractions; 8 – target; 9 – area of erosion; 10 – magnets.

The shape of the target surface (figure 2) can be explained by the non-uniformity of the plasma localization above it, which in turn is due to inconsistency in the ion current density. The erosion area of the target is therefore directly proportional to the ion current density, with the lowest point in its topography coinciding with the highest sputtering rate, whereas at the highest points the rate is zero. This means that in effect the sputtering rate can be considered directly proportional to the topography of the erosion area.

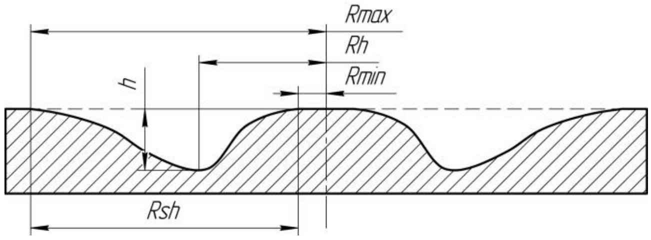

Figure 2. Erosion area of a magnetron sputtering source target: Rmax – peak radius; Rmin – minimum radius; Rh – distance to the lowest point; Rsh – width of erosion area; h – depth of erosion area.

The distribution of magnetron sputtered material occurs in accordance with the law of cosines to a degree of *n* [3], a coefficient which is determined by:

- The material, uniformity, grain dimensions and structure of the target, which represent the most significant factors [4].
- The influence of electric and magnetic fields on the trajectory of the sputtered material's ionized atoms.
- The collision of sputtered atoms with each other and with the working gas.
- An absence of sputter atom condensation at the point of impact with the substrate
- Variation in the target material and the density of the deposited film.

Experimental calculations of n for various targets, magnetron sputtering sources and modes of deposition suggest a typical range of between 0.4 and 1.7 [3]; however, computer simulation can take into account a greater of parameters [5, 6].

3. Mathematical description

The thickness of a film deposited by source evaporation from a point source can be determined for any given location on the substrate δ (figure 3) by:

$$h = \frac{dq_u(\varphi,\theta)}{\rho dA_0} = \frac{q_u \cos(\varphi)\cos(\theta)}{\pi C^2 \rho}\ \text{m},$$

where ρ is the thickness of the material, q_u is the weight of sputtered or evaporated material in kg, ϕ is the angle between the direction of evaporation and the selected point on the substrate, C is the distance and θ is the angle of deposition material.

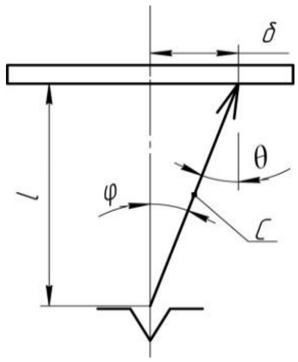

Figure 3. Geometric scheme for calculating the thickness of a film produced by magnetron sputtering from a point source.

As the process of magnetron sputtering occurs in the erosion area, the uniformity of the film needs to be calculated from the various different point sources that exist within this area. This is because each point has its own sputtering rate, which is directly proportional to the erosion area's topography. This topography is determined mostly by plasma localization above the surface of the source; and consequently, depends on the magnetic field. Calculation of the topography based on measurements of the magnetic field therefore allows for a prediction error of 15 % for balanced magnetron sputtering sources and 25 % for unbalanced magnetron sputtering sources [9]. To reduce this error, the topography of the erosion area has instead been measured directly; a method which has had some success by allowing individual points to be connected by cubic splines (figure 4).

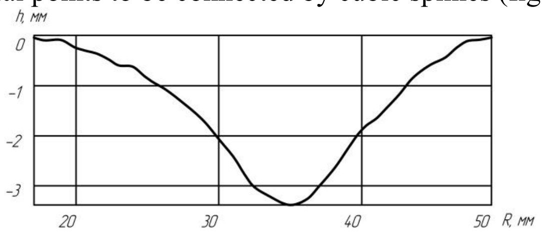

Figure 4. Erosion area of a magnetron sputtering source.

Owing to the fact that calculation of the degree of non-uniformity in the film thickness relates directly to the maximum thickness, the constants in the formula can be omitted. The magnetron sputtering shown in figure 5 can therefore be described mathematically by:

$$T(r,t) = \int\limits_{\alpha}\int\limits_{R} \frac{\cos^n(\varphi(R,r,\alpha,t)) \cdot \cos(\theta(R,r,\alpha,t)) \cdot \sqrt{1+(f_R'(R,t))^2} \cdot g(R,t) \cdot R}{C(R,r,\alpha,t)^2}\, dR d\alpha$$

where r is the distance to the point at which non-uniformity is calculated, t is the time, R is the radius of the erosion area (which changes from $Rmin$ to $Rmax$), α is the angle of integration in the cylindrical coordinates (which changes from 0 to 2π), n is the coefficient for the target magnetron sputtering source and process parameters, ϕ is the angle of particle motion relative to the normal of the erosion area surface, θ is the angle of particle motion relative to the normal to the substrate surface, $f(R)$ is a function of the erosion area topography, $g(R)$ is a sputtering rate function, and C is the distance between the sputtering point and deposition zone.

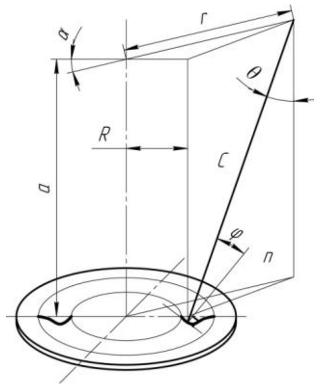

Figure 5. The geometry of the calculation for determining the non-uniformity in a coating produced by magnetron deposition.

This formula for determining the non-uniformity of a coating can be determined as:

$$P(r,t) = \frac{T(r,t)}{T(0,t)}$$

Note that this simplification assumes that the degree of reverse sputtering is zero, and is only applicable in instances where the entire substrate is in the area of erosion.

To determine the cosine degree, it is necessary to first carry out a series of experiments under a given set of parameters to determine the thickness of the film deposited, with subsequent calculation being complicated by its dependence on many factors. Determining the topography of the sputter target requires experiments over long periods of time, creating a need to instead estimate how the erosion area affects the uniformity of coating.

4. Computer simulation

The magnetron sputtering model developed was designed to approximate the vacuum coating system VUP-11M located at the Electronic Technology in Engineering department of BMSTU. The diameter of the magnetron is 100 mm, and a measured area of its target erosion was used in the simulation (figure 4). All simulation was carried out using the program MathCad, with calculations being performed based on a substrate to target distance of 100 mm (figure 6).

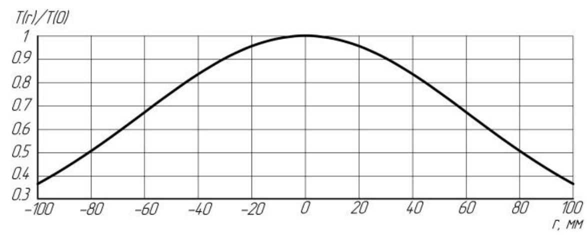

Figure 6. Graph of the uniform coating generated by a 100 mm diameter magnetron sputtering source at a distance of 100 mm from the target.

Simulation was conducted based on equation 1 of the coating uniformity achieved by sputtering a target with an erosion area (figure 4), without an erosion zone (i.e., a new target), and without an erosion area but taking into account the sputtering rate. The results obtained (Table 1) show that without an erosion area and registration of the rate distribution *g*, the non-uniformity of the coating is increased (0.4 % at a distance of 50 mm, 0.7 % at 100 mm, 0.5 % at 150 mm.). Meanwhile, increasing the minimum depth of the erosion area from 0 reduces this non-uniformity, which means that a target without erosion will produce a far less uniform coating than a target that is eroded.

Table 1. Simulation of the coating non-uniformity generated by magnetron sputtering (magnetron diameter of 100 mm, distance of 100 mm).

Distance from the target's centre	With erosion area and sputtering rate distribution accounting	Without erosion area (new target) but with sputtering rate distribution accounting	With erosion area, but without sputtering rate distribution accounting	Without erosion zone and sputtering rate distribution accounting
50 mm	24,2%	24,7%	24,3%	24,6%
100 mm	63,3%	64,1%	63,5%	64,0%
150 mm	84,5%	85,0%	84,6%	85,0%

5. Conclusions

On the basis of the computer simulation results presented it can be said that increasing the erosion area has a negligible (<1%), but nevertheless positive, effect on the uniformity of a magnetron sputtered coating. This, of course, assumes that the entire substrate is within the area of erosion. The development of deposition parameters for obtaining a desired uniformity therefore needs to consider not just the erosion area and the sputtering rate distribution, but also the fact that the increase in erosion area over time will improve the coating's uniformity.

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