*Vacuum*/volume 38/numbers 8–10/pages 791 to 794/1988
Printed in Great Britain

0042-207X/88$3.00+.00
Pergamon Press plc

# Film thickness distribution in magnetron sputtering

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*Of crucial importance to the thin film process engineer is an understanding of the parameters which affect the film thickness distributions which may be obtained from magnetron sources. This paper describes how variations in source design, target erosion and source-to-substrate distance affect observed uniformities from a magnetron source. A simple method of simulating magnetron sources using target erosion data is described. Film thickness distributions for circular planar magnetrons are shown for a number of different source–substrate distances and for various target erosion patterns. The implications of these results to the design of magnetron sources and to the process engineer are discussed.*

## 1. Introduction

The film thickness distribution which can be obtained from diode and magnetron sputtering sources is of interest to process/development engineers and to the designers of sources and coating systems. The thickness uniformity bears a direct influence on useable substrate size and overall process economics. A better understanding of source behaviour and the way it affects subsequent film uniformities leads to better source design and improved sputtering apparatus. The aim of this paper is to show how relatively simple calculations by computer, based upon standard emission equations, can successfully describe the film thickness uniformities which may be obtained from magnetron sources of different designs.

This paper describes how calculations of emission from circular magnetrons can be used to predict film thickness uniformities and how these calculations can be used to examine the effect of varying target erosion profiles on subsequent film thickness uniformity. Comparisons of calculated and measured data show validity of the technique.

## 2. Background

The film thickness obtained from any source depends on the geometry and area of the source, its characteristic emission behaviour (e.g. cosine or point source), the ambient pressure, distance between source and substrate, substrate geometry and relative motions between source and substrate. A circular magnetron source has an erosion groove (Figure 1) which is caused by the magnetic confinement of electrons into a toroid above the target surface. This groove shape is mainly dependent on magnetic field strength, magnetic field shape and target material and is controlled primarily by the magnetron design. The position and shape of this groove directly affects the film thickness distribution obtained on the substrate[1].

A description of source emissions is given by Holland[2]. These models have been further developed and expanded to cover a wide variety of source–substrate geometries including domed workholders and a variety of source types including relative motion[3,9]. Using these equations it has been possible to predict film uniformities and to design mask shapes to intercept material between source and substrate to provide improved uniformity[7,8].

The approach used here is to use the equations for a surface source onto a planar rotating workholder[2]. The calculation involves the summation of deposited material onto a rotating workholder by integrating the emission from a surface source over 360° for the geometry shown in Figure 2. Equation (1) was derived by Holland[2] and by another route by Behrndt[9]. The thickness of the deposited film, $t$, can be described by equation (1)

$$t = \frac{m_x h^2(h^2+r^2+a^2)}{\rho\pi(h^2+r^2+a^2+2ar)^{1.5}(h^2+r^2+a^2-2ar)^{1.5}} \quad (1)$$

where $m_x$ = mass of material; $\rho$ = density; $h$ = source to substrate distance; $R$ = radius of source ring; $a$ = position on substrate; $t$ = thickness of film.

This same equation can also be used for calculating a continuous surface ring source onto a stationary substrate.

## 3. Theoretical

A computer program called UNIF has been written to calculate values of film thickness based upon equation (1). The program calculates the film thickness at a given position on the substrate

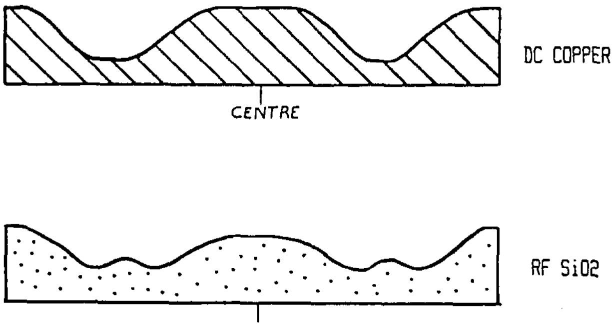


**Figure 1.** Typical erosion profile; magnetron target.

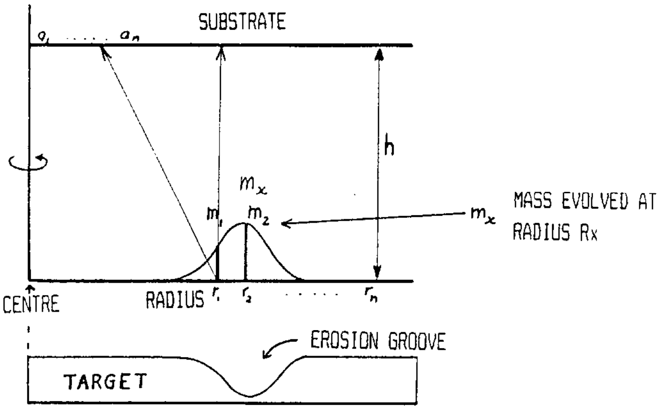


**Figure 2.** Schematic of geometric set-up showing parameters entered into equation (1)

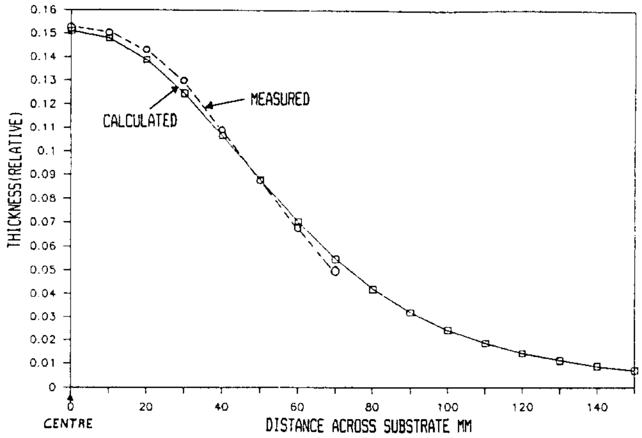


**Figure 3.** Film thickness distribution 100 mm magnetron; comparison of calculated and measured.

by summing the calculated thicknesses at that position, resulting from emissions at various radii across the target (Figure 2). The calculations are then repeated for further positions on the substrate. In this way the film thickness across the substrate is calculated point by point.

The program works by the summation of a large number of ring sources of different radii with each radius allotted a weighted emission value ($m_x$) corresponding to the erosion pattern on a target (Figure 2).

The value of $m_x$ which is inserted in equation (1) is the mass of material emitted over the circumference of erosion track. This can be calculated from the erosion depth profile, multiplied by the radius at that point. The UNIF program does this automatically and so it is only necessary to input values of $m_x$ corresponding to the erosion pattern.

Since calculation time is only 1–2 min it is possible to feed in a variety of erosion patterns and observe the effect on film thickness, enabling rapid assessment of magnetron designs or changes in process parameters such as source to substrate distance.

## 4. Experimental

Deposits of Cu were made in an Edwards ESM100 sputter coater onto water-cooled glass substrates. Films were produced from the Edwards 100 and 150 mm magnetron cathodes and thickness was measured on the glass substrates by the step-edge technique using a Rank Taylor Hobson Talystep. Process pressure was $5 \times 10^{-3}$ mbar; powers of 1 kW dc and 2 kW dc were used for the 100 and 150 mm magnetrons, respectively. Calculated and measured thicknesses were superimposed to assess agreement.

## 5. Results and discussion

Figures 3 and 4 show a comparison of calculated and measured results for the 100 and 150 mm magnetron sources. The calculated thicknesses are normalised to the measured graphs. This is because measured mass values were not used in these thickness calculations as film thickness distribution is independent of the values of $m_x$. Results show a good agreement between calculated and measured uniformity for these two sources. The measured data gives slightly better uniformity than the calculated values suggesting that either the emission characteristics are not exactly cosine or that other effects such as gas scattering are occurring. However, the agreement gives confidence to examine other source geometries.

Figure 5 shows the result of calculating the film thickness for a diode source. In this case the same value of $m_x$ at all radii was used, i.e. an even erosion across the disc. The 'E' marked on Figure 5 shows the position of the edge of the source. For completeness, calculations were also made at 20, 10 and 5 mm source–substrate distances although in practice the source would not function at these distances.

Figure 6 shows the results of calculating film thickness for the Edwards 200 magnetron using actual emission data as measured by erosion groove shape. The insert on the figure shows the source emission data used in the program. The graphs at various source to substrate distances show the behaviour of a typical ring source[2]. At 30 mm source to substrate distance a peak in film thickness is observed at a radius corresponding to the radius on the target of maximum erosion. As the source–substrate distance is increased areas of substantial uniformity can be obtained.

Figure 7 shows the film thickness calculated for the 150 mm magnetron data using two separate target erosion patterns with the same radius of maximum erosion. It is interesting that the erosion pattern with the wider area of target usage gives the

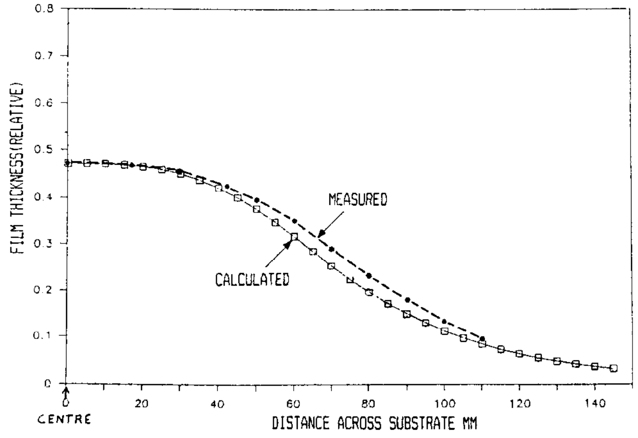


**Figure 4.** Film thickness distribution 150 mm magnetron; comparison of calculated and measured.

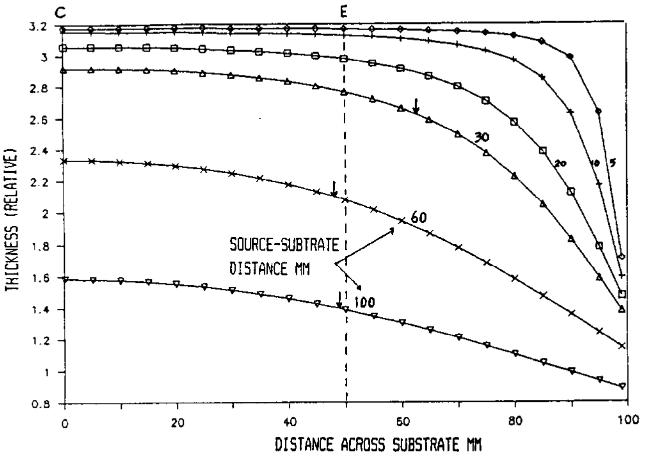


**Figure 5.** Calculated film thickness distribution: 100 mm diode source.

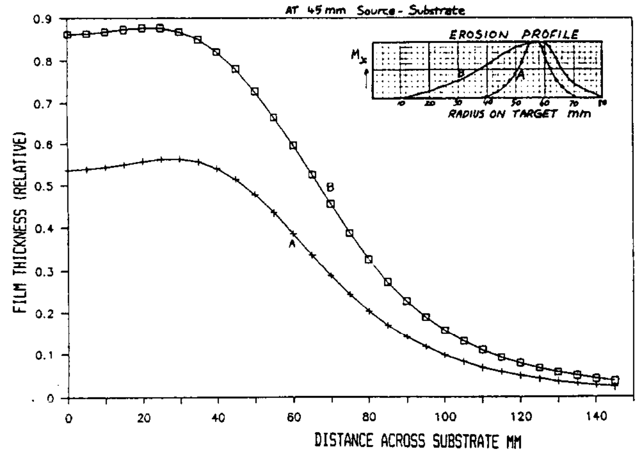


**Figure 7.** Calculated film thickness distribution: 150 mm magnetron—different wear pattern.

worse overall thickness distribution at that source to substrate distance. The amount a target wears is of importance to the magnetron user and to the designer. The 'target utilisation' is of importance to the user because (a) expensive target material is not wasted and (b) there is less machine downtime. It can be seen that the best target utilisation does not necessarily give the best film thickness uniformity and therefore a compromise has to be made in design.

The erosion pattern and subsequent uniformity are linked uniquely with the source to substrate distance as shown in Figure 6. Therefore it is not possible to directly compare the film uniformities obtained for a given erosion pattern unless the source to substrate distance is taken into account. This is illustrated by the following example where film thicknesses have been calculated for two erosion geometries. Figure 8 shows the results. Erosion profiles A and B have been used to calculate uniformities. Profile A is a conventional single magnetron erosion groove with relatively low target utilisation and profile B is a double ring erosion groove produced by a double ring of permanent magnets in the magnetron design. (The actual erosion is hypothetical and not measured in this illustration.)

Figure 8 shows calculated film thicknesses for a range of source to substrate distances. At 80 mm source to substrate distance it is clear that erosion B gives a worse uniformity. This is in agreement with Figure 7 where it was demonstrated that a target with more utilisation towards the centre gives a worse film thickness uniformity. At 60 mm source to substrate distance the two graphs differ, notice the A distribution is benefiting from the special advantages of the ring source geometry by having a slight dip at the centre but overall giving a better uniformity. However, this situation changes at 40 mm source to substrate distance. Profile A uniformity has now worsened to the point of not being useful for many sputtering applications, but profile B uniformity continues to improve. Finally at 30 mm source to substrate distance the B profile uniformity is much better than that for A.

The most uniform film thickness is only achieved if the source to substrate distance is suitably selected. To know that source to substrate distance requires repetitive experimentation which is very time consuming. The UNIF computer simulation used here enables a rapid assessment of target erosion characteristics desired for a given application and is of considerable benefit to the magnetron designer. Similarly when a process engineer is

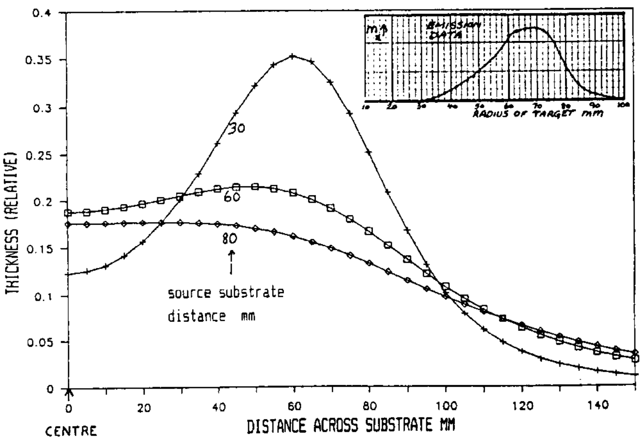


**Figure 6.** Calculated film thickness distribution: 200 mm magnetron.

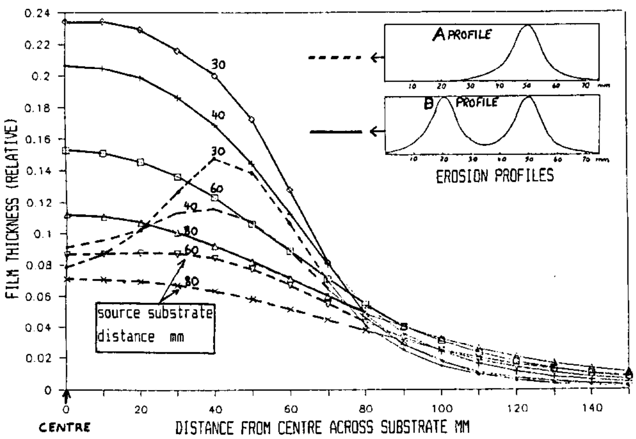


**Figure 8.** Film thickness distribution for different erosion patterns at various source to substrate distances.

using a magnetron of known erosion pattern it is simple to model the behaviour for a range of source to substrate distances. This method of modelling is therefore a very convenient tool.

## 6. Conclusions

(1) A computer program using simple formulae based upon cosine emission characteristics has been used to calculate deposition from 'multiple' ring sources. This situation corresponds to a circular magnetron geometry.

(2) The calculations agree well with the measured film thickness data from magnetrons giving a qualitative agreement.

(3) A program to calculate film uniformities for different erosion geometries depending on source to substrate distance has been demonstrated.

(4) This simple technique is useful is designing and using circular sources saving much process development time.

## Acknowledgements

The author wishes to express his thanks to the directors of Edwards High Vacuum International for permission to publish this paper.

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