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Eliminating the hysteresis effect for reactive sputtering processes

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Reactive sputter processes frequently exhibit stability problems. The cause of this is that these processes normally exhibit hysteresis effects in the processing curves. Eliminating the hysteresis would significantly simplify the use of reactive sputtering processes. So far the only known way of eliminating the hysteresis is to increase the pumping speed to unrealistically high values. By an increased understanding of the process we have realized a fully realistic technique to eliminate the hysteresis for reactive sputtering processes. By simply reducing the size of the target sputter erosion zone below a critical value, simulations predicted that hysteresis should be eliminated. This has been experimentally verified for reactive sputtering of Al in an Ar/O_2 atmosphere. The fundamental explanation to this behavior as well as the experimental verification are presented. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1906333]

The erosion rate of a sputtering target depends primarily on the applied target ion current and the sputtering yield. During reactive sputter deposition the supply of the reactive gas will change the chemical composition of the target surface thereby altering the sputter erosion rate. Due to the latter also the voltage-current characteristics of the sputtering glow discharge plasma will change. These are complicating factors in controlling reactive sputtering processes. In fact most reactive sputtering processes respond in a hysteresis manner to input processing parameters.[1,2] So far the only known way of eliminating this hysteresis has been to increase the pumping speed to unrealistically high values. Therefore this method for eliminating the hysteresis is hardly not used at all.

A way to design a system where this hysteresis is eliminated has been identified. By theoretical process modeling, using the Berg model,[3,4] we have found that this is indeed possible by utilizing a small sputter erosion area. In this article, we present the cause of the hysteresis elimination as well as experimental verification of the phenomena.

The experiments were performed in a cylindrical vacuum chamber, 44 cm in diameter and 70 cm in height. A 15 cm diameter Al plate was used as a sputtering target mounted onto a water cooled magnetron in the top of the chamber. The target current was supplied using a pulsed dc arc surpression power supply from company ENI. Prior to the measurements the chamber was evacuated by a turbomolecular pump to a base pressure of about 10^{-6} Torr. The turbomolecular pump was throttled to obtain the desired pumping speed. Ar gas was introduced into the chamber to a pressure of 20 mTorr and the reactive gas O_2 was introduced using a thermal mass flow regulator. The processing pressure was recorded using an *x-t* plotter connected to the dc output from a capacitance manometer. The partial pressure of the reactive gas was determined by substracting the constant Ar pressure from the processing pressure.

Two magnetic configurations were used for the magnetron: A standard, weakly unbalanced magnetic assembly and a small, magnetic assembly, that also could be rotated in a circular path inside the magnetron housing. The circulation allowed the two magnetic setups to run at the same maximum power with respect to target cooling. These two magnetic configurations gave rise to erosion tracks on the target with an approximate diameter of 9 and 2.5 cm, respectively. The smaller erosion track is estimated to be around 20 times smaller.

The Berg model for the reactive sputtering process describes in a simplified way the behavior of the reactive sputtering process under steady state conditions.[3,4] The model assumes a uniform partial pressure (P) of the reactive gas in the chamber. It is also assumed that all material is uniformly sputter eroded from the target erosion area (A_t). Typical calculated curve for P as a function of supplied reactive gas flow (Q) is shown in Fig. 1. The solid S-shaped curve is only obtained experimentally if the process is carried out with a fast feedback control system of P. Without a feedback control system and using Q as the control parameter the system

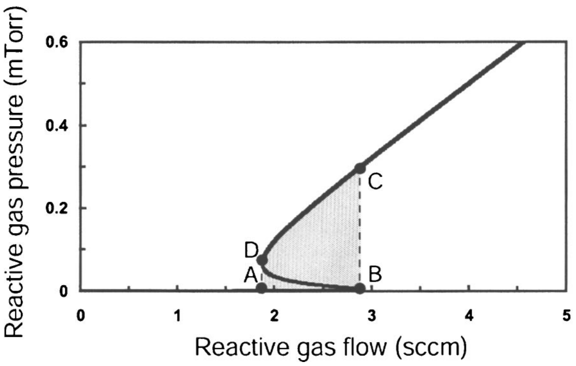

FIG. 1. Calculated reactive gas partial pressure P vs supply of the reactive gas Q. The avalanche positions B-C and D-A define the hysteresis width of the process also marked by dashed lines and shadowed area.

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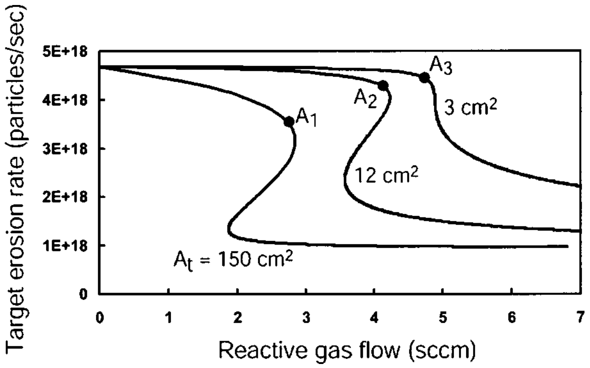

FIG. 2. Calculated sputter erosion rates vs supply of the reactive gas for different target (=effective sputter erosion) areas. The unit of the erosion rate is sputter eroded particles/s. The indicated points A_1, A_2, and A_3 correspond to preferred experimental processing points.

will avalanche from B to C for increasing values of Q and avalanche from D to A for decreasing values of Q. The avalanche positions B-C and D-A define the hysteresis width of the process. This width is marked by the dashed lines and shadowed area. As long as the solid line exhibits a S-shape the process is defined (and behave) as a hysteresis process.

It has earlier been reported, by Serikawa and Okamoto,[5] that the pumping speed (S) of the external vacuum pump in the system is of critical importance to the shape of the processing curves. Increasing S will decrease the width of the hysteresis region and at a critical value for the pumping speed the hysteresis will in fact be eliminated. Unfortunately the pumping speed needed to eliminate the hysteresis is normally far too high to be realized

In all planar sputtering systems the area of the target sputter erosion zone A_t is smaller than the deposited area (A_c). In the calculations of Fig. 1 it was assumed that A_t and A_c were 150 and 2500 cm^2, respectively. In Fig. 2 calculated target erosion rate (R) versus Q curves for different values of A_t are plotted when the target ion current is 0.5 A. Here we clearly see that the calculations predict that the S shape of the curves can be affected and eliminated by decreasing A_t to small values. Consequently the calculations predict that it is possible to obtain hysteresis free reactive sputtering simply by decreasing the target size.[6] Experience has shown that the preferred experimental processing points are A_1,A_2, and A_3 for the curves in Fig. 2. Notice that the total sputter erosion rate is greater for the small target (A_3) than for the large target (A_1) for the same target current. Calculations also predict (not shown here) that decreasing the sputter erosion area will result in an increase of the difference between the compositions of the target surface and the growing film, in such a way that the target becomes more and more metallic and the growing film becomes more and more compound rich (closer to stoichiometric compound). This feature, together with the nonhysteresis behavior, is close to the ideal reactive sputtering process.

Calculations of the gettering of the reactive gas inside the processing chamber (Q_G) and the throughput (Q_P) of reactive gas to the external vacuum pump (pumping speed S) as a function of reactive gas partial pressure may illustrate the mechanism for eliminating the hysteresis by decreasing the target area. Calculation results are shown in Fig. 3. The total supply of the reactive gas (Q) is the sum of the throughput to the external pump Q_P and the gettering in the chamber Q_G. The straight line, corresponding to the throughput to the pump Q_P will be unaffected by a change in target size. The effect of decreasing the target size is shown to decrease the maximum negative slope of the Q_G versus P curve. Below a critical target size this negative slope will become smaller than the positive slope of the straight line for the pumping speed. Consequently the resulting Q versus P curve will have no negative slope and the process will not exhibit any hysteresis. This defines the proposed principle to generate hysteresis free reactive sputtering processes. It should be understood that this effect is not caused by an increase of the target current- or power-density. Increasing the power to the target will increase the sputter erosion rate at the target area as well as the deposition rate at the deposited areas. This will not, however, change the ratio of the reactive gas gettering at these two areas. The increased power implies more gettering of reactive gas Q_G, which pushes the Q_G versus P curve upward but at the same time the increased power density pushes the curve to the right. The combined effect is that the shape of the curve (negative slope) is unaffected and the hysteresis will therefore not be eliminated by an increase of the target power. However, decreasing the target surface (at constant power) will only marginally push the Q versus P curve upward. Here the total power is constant while the power density is increased. Consequently, the Q_G versus P curve is pushed to the right which gives a reduced negative slope and subsequently a reduced hysteresis. In this way it is possible to obtain favorable hysteresis free processing condition.

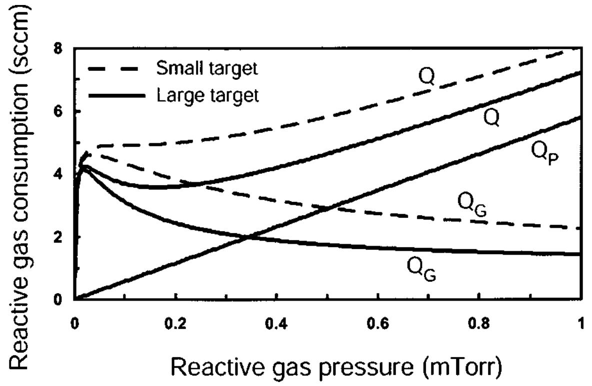

FIG. 3. Calculated curves Q vs P, Q_P vs P, and Q_G vs P for a small and a large area target.

Experiments were carried out to verify these theoretical findings. In Fig. 4 are shown the measured P as a function of Q for the large and the small targets, respectively. The curves

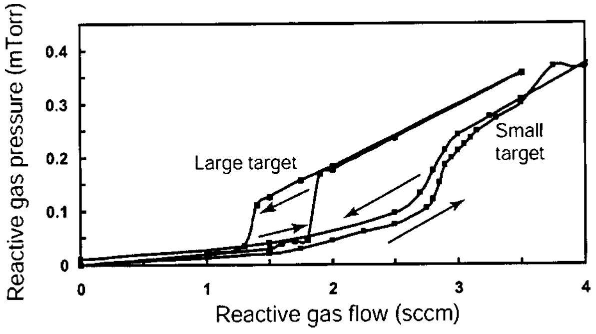

FIG. 4. Experimental results for reactive gas partial pressure P vs supply of the reactive gas Q for a small and a large area target.

were taken under identical processing conditions (pumping speed, target current, target material, etc.). It is clearly indicated that the hysteresis is eliminated for the small sized target. Also the deposition rate was found to be higher for the smaller sized target. These results strongly support the theoretical predictions.

The focused power dissipation caused by the small target erosion zone may be evenly distributed over the whole target surface by moving the magnets inside the target assembly. An additional experiment showed that the process was hysteresis free also under such moving magnets conditions (0.4 rounds/s).

It has been shown that it is possible to obtain hysteresis free reactive sputtering from a small sized planar target. Experimental results verify the theoretical predictions of the behavior of such a process. To distribute the power dissipation and to allow for a high rate deposition a system with a small moving magnet may be used. With this technique it is possible to obtain hysteresis free reactive sputtering process acting on a large target area.

[1] I. Safi, Surf. Coat. Technol. **127**, 203 (2000).
[2] S. Berg, T. Nyberg, H.-O. Blom, and C. Nender, *Handbook of Thin Film Process Technology* (Institute of Physics Publishing, Bristol, UK, 1998).
[3] S. Berg, H.-O. Blom, T. Larsson, C. Nender, J. Vac. Sci. Technol. A **5**, 202 (1987).
[4] S. Berg, T. Larsson, C. Nender, and H.-O. Blom, J. Appl. Phys. **63**, 887 (1988).
[5] T. Serikawa and A. Okamoto, Thin Solid Films **101**, 1 (1983).
[6] S. Berg and T. Nyberg, Patent No. WO 03/006703A1 (2001).