Elucidating the asymmetric behavior of the discharge in a dual magnetron sputter deposition system

M. Yusupov,[1,a)] E. Bultinck,[1] D. Depla,[2] and A. Bogaerts[1]
[1]Department of Chemistry, Research Group PLASMANT, University of Antwerp, Universiteitsplein 1, 2610 Antwerp, Belgium
[2]Department of Solid State Sciences, Research Group DRAFT, Ghent University, Krijgslaan 281 (S1), B-9000 Ghent, Belgium

(Received 10 February 2011; accepted 14 March 2011; published online 31 March 2011)

A magnetron discharge is characterized by drifts of the charged particles' guiding center, caused by the magnetic field, in contrast to unmagnetized discharges. Because of these drifts, a pronounced asymmetry of the discharge can be observed in a dual magnetron setup. In this work, it is found that the shape of the discharge in a dual magnetron configuration depends on the magnetic field configuration. In a closed configuration, strong drifts were observed in one preferential direction, whereas in a mirror configuration the deflection of the discharge was not so pronounced. Our calculations confirm experimental observations. © *2011 American Institute of Physics*. [doi:10.1063/1.3574365]

A dual magnetron configuration consists of two magnetrons in one reactor. It is used, for example, to enhance the process stability in industrial coaters where the power is switched between two cathodes consisting of the same material.[1] A second application is the deposition of alloys or complex oxides (see, e.g., Refs. 2–4).

There are two following possible magnetic field configurations in a dual magnetron setup: a closed or a mirror configuration. In a closed magnetic field configuration, the magnets of both magnetrons are mounted in the opposite way; the magnetic field lines go from one target to the other, so that the generated discharge is only confined between the targets of both magnetrons. In the case of a mirror configuration, the magnets of both magnetrons are mounted in the same way; the magnetic field lines go from the targets to the substrate, resulting in the formation of two separated discharges. This is nicely demonstrated by Musil and Baroch.[5]

In a dual magnetron, an asymmetric behavior of the discharge is observed experimentally,[6] which is not yet completely understood. This asymmetry is probably caused by drifts of the charged particles' guiding center, and it can influence the discharge characteristics. Therefore, there is a need to deeply investigate these drifts and their effect on the plasma characteristics.

To elucidate the origin of this preferential drift of charged particles, a Monte Carlo (MC) model was developed to investigate the behavior of the fast electrons in an Ar/O_2 direct current (dc) dual magnetron discharge. In a MC model, the particles (i.e., in this case electrons) are represented by a limited ensemble of superparticles, which are followed during their movement in the electric and magnetic fields. Their collisions are described by the MC collision algorithm. A detailed overview of the electron MC model can be found in Refs. 7–10.

When magnetic and/or electric fields are present, the charged particles' motion will be influenced by different types of guiding center drifts.[11,12] Due to their lower mass, mainly electrons will be influenced by the magnetic field, and therefore we only focused on the electrons in this study. There are following three important drifts in a magnetron discharge:

(1) *Electric field drift:* $\mathbf{v}_E=(\mathbf{E}\times\mathbf{B}/B^2)$. This drift is caused by perpendicular electric and magnetic fields. The direction of the drift is determined by the vector product of these fields. Due to the electric field drift the electrons perform helical movements perpendicular to both **E** and **B**.

(2) *Gradient B (grad-B) drift:* $\mathbf{v}_{\nabla B}=[(W_\perp/q)(\mathbf{B}\times\nabla B/B^3)]$. This drift occurs when the magnetic field varies in magnitude, causing a gradient in one direction. Such configuration causes a change in the gyro radius during one gyro period. Thus, a drift is created perpendicular to both **B** and grad-B. The direction of this drift depends on the charge of the particle.

(3) *Curvature drift:* $\mathbf{v}_R=[(2W_\parallel/q)(\mathbf{R}_c\times\mathbf{B}/R_c^2B^2)]$. This drift happens when the magnetic field varies in direction. If a magnetic configuration characterized by curved force lines with an equal curvature can be realized, a guiding center drift arises from the centrifugal force, $\mathbf{F_{cf}}$, felt by the charged particle as it moves along the magnetic field line. The direction of the drift is perpendicular to both **B** and the curvature force, and depends on the particle's charge.

In these formulas, q is the elementary charge, $W_\perp, W_\parallel$ are kinetic energies of the electron, perpendicular or parallel to the magnetic field line, respectively, m is the electron mass, R_c is the radius of the curvature of the magnetic field line, and **E** and **B** are the electric and magnetic field, respectively. Besides the three drifts mentioned above, also polarization and general force drift are possible,[11,12] but they are less important in direct current (dc) magnetron discharges.

The dual magnetron setup under study consists of two magnetrons positioned at angles of 45° with respect to the substrate, and is schematically presented in our previous work.[7] It operates in dc mode, in an Ar/O_2 mixture at 300 K with partial pressures of 1 Pa Ar and 0.24 Pa O_2. The two

a)Electronic mail: maksudbek.yusupov@ua.ac.be.

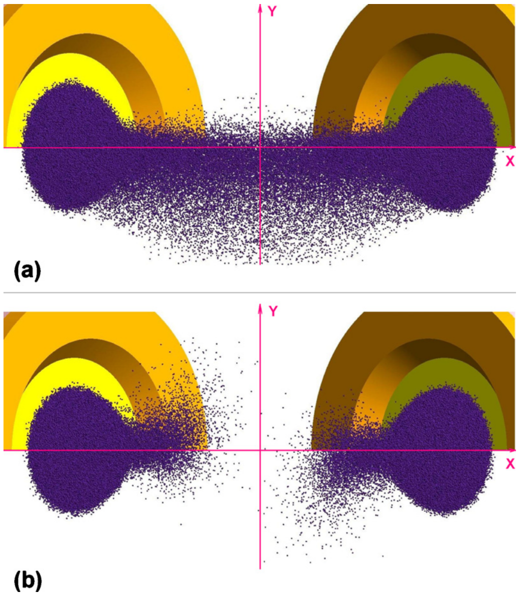

FIG. 1. (Color online) Top view of the dual magnetron setup, showing the positions of the Ar^+ ions, formed by electron impact ionization, in the case of a closed (a) and mirror (b) magnetic field configuration.

targets are made of Ti, with a radius of 25 mm. The electric and magnetic fields (both for a closed and a mirror configuration) are needed as input in the model, and are also presented in Ref. 7.

The positions of the Ar^+ ions, which are created by electron impact ionization, are shown for both magnetic field configurations in Fig. 1, when looking down at the plane of the target origins (xy-plane). It is clear that in the closed magnetic field configuration most of the ionization occurs in the –y part of the dual magnetron reactor, i.e., most of the electrons (and Ar^+ ions) are located on this side [see Fig. 1(a)]. This is in agreement with experimental results obtained by Baroch and Musil.[6] In the case of the mirror configuration, an asymmetry in one magnetron region is observed; for the left magnetron most ions (and therefore most electrons) are located in the +y part of the dual magnetron reactor and for the right magnetron in the –y area [see Fig. 1(b)]. For this case there is a symmetry with an inversion point located in the center of xy-plane [see Fig. 1(b)]. There are no experimental observations reported in literature for this configuration.

To investigate the reason of these preferential movements in the y direction, the separate drift velocities are studied. Figure 2 illustrates the y-component of the electric field drift ($\mathbf{v}_E$) for both magnetic field configurations, plotted in the xz-plane. Note that the surface plots are taken at y $=0$ m (i.e., the symmetry plane of the dual magnetron reactor). The values of $\mathbf{v}_E$ near the targets are very high (i.e., around 4.5×10^6 m/s; cf. Fig. 2), and they are the same for the closed and mirror configuration. No asymmetry is observed here, as a result of the uniformity and symmetry of the magnetic field in this region (see also Fig. 1). However, in the region between both magnetron areas, a different behavior is observed for the closed and mirror configuration. For the closed configuration [Fig. 2(a)], it is clear that $\mathbf{v}_E$ reaches values in the order of 2000–5000 m/s in –y direction in the region between the two magnetron areas, whereas in the outer regions it can reach values up to 5×10^4 m/s, but

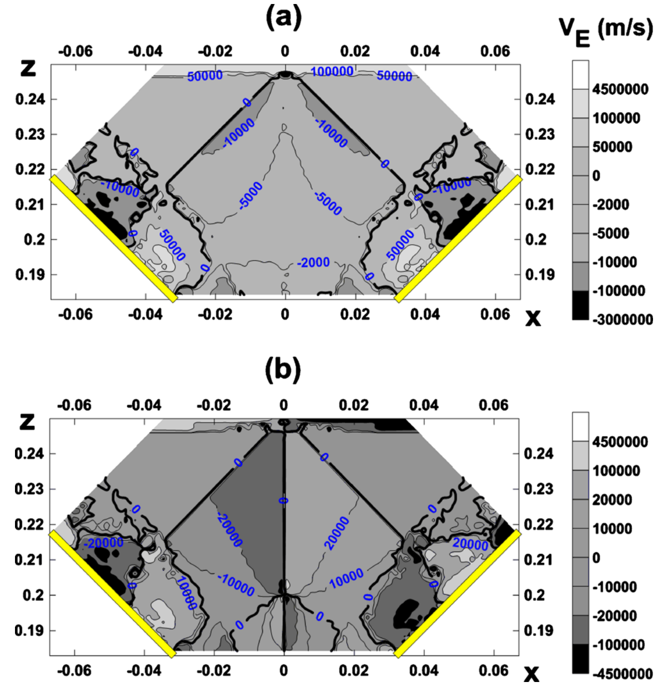

FIG. 2. (Color online) Calculated y-component of the electric field drift velocity, plotted in the xz-plane, at y=0 m, in the case of a closed (a) and mirror (b) magnetic field configuration.

in the +y direction. In the mirror configuration [Fig. 2(b)], the magnitudes of $\mathbf{v}_E$ in the region between both magnetron areas are in the order of $1-2\times10^4$ m/s, but in the –y direction for the left magnetron and in the +y direction for the right magnetron.

The two-dimensional profiles of the y-component of the grad-B drift ($\mathbf{v}_{\nabla B}$) are plotted in Fig. 3 (again in the xz-plane, at y=0 m) for both magnetic field configurations. In the closed field configuration [Fig. 3(a)], $\mathbf{v}_{\nabla B}$ is mainly directed

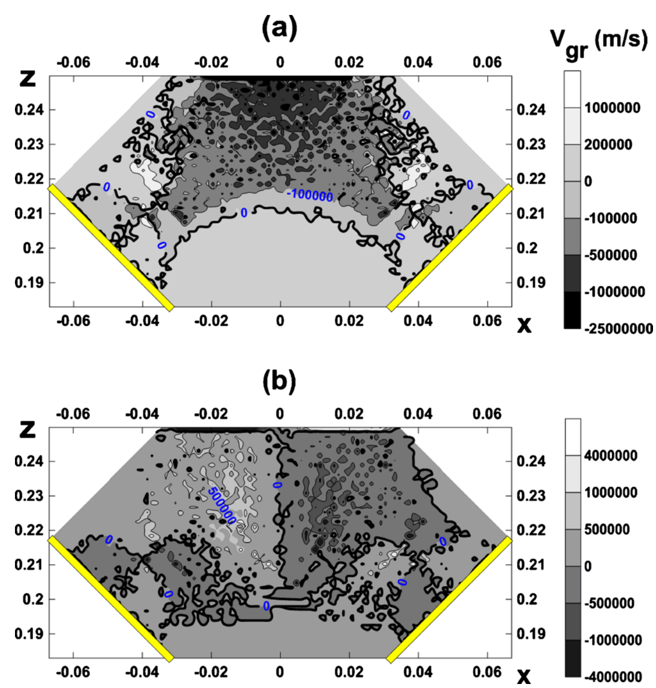

FIG. 3. (Color online) Calculated y-component of the grad-B drift velocity, plotted in the xz-plane, at y=0 m, in the case of a closed (a) and mirror (b) magnetic field configuration.

in the –y direction in the area between the left and the right magnetron, and typically reaches values in the order of 10^5 m/s (up to 10^6 m/s), which is much higher than the corresponding $\mathbf{v}_E$ values. This means that the electrons will be pushed strongly toward the –y direction in almost the whole area where the plasma is located. This is indeed clearly observed in Fig. 1(a). In the case of the mirror field configuration [see Fig. 3(b)] we can see a symmetry of $\mathbf{v}_{\nabla B}$ with an inversion point on z axis in the bulk area: above the left magnetron $\mathbf{v}_{\nabla B}$ is pointing to the +y direction, and at the right magnetron it is pointing to the –y direction. The magnitude of $\mathbf{v}_{\nabla B}$ can reach values up to 5×10^5 m/s, which is also larger than the corresponding $\mathbf{v}_E$ drift values [Fig. 2(b)]. Therefore, also in the mirror configuration, the electrons will drift according to the $\mathbf{v}_{\nabla B}$ directions, but the effect will be slightly compensated by the $\mathbf{v}_E$ drift, pointing in the opposite direction. The electron drift to the +y direction for the left magnetron, and the drift to the –y direction for the right magnetron were indeed observed in Fig. 1(b).

Estimating the values of the curvature drift ($\mathbf{v}_R$) is rather difficult, because the radius of the curvature of the magnetic field line (R_c) and its components in x, y, z directions cannot easily be determined. However, we can roughly estimate the direction of $\mathbf{v}_R$ and the magnitudes in some points. In the case of the closed field configuration, the pronounced curvatures of the magnetic field lines are located in the region between the two magnetrons (see also the presentation of the magnetic fields in Ref. 7). We have analytically (approximately) estimated that in the central area (around x=0 m) the values of $\mathbf{v}_R$ are between 50 and 500 m/s, and the direction of $\mathbf{v}_R$ in the bulk area is toward the –y direction. In the case of the mirror field configuration (see also Ref. 7), the magnitudes of $\mathbf{v}_R$ are approximately the same as in the closed field configuration, but the directions are in opposite way from each other; for the left side it goes to the +y direction, and for the right it goes to the –y direction. Since these $\mathbf{v}_R$ values are very small, we expect that $\mathbf{v}_R$ will not contribute to the total drift of the electrons.

In conclusion, an MC model was developed to study the electron behavior, and to investigate the three most important contributions to the electron drift, i.e., electric field drift, gradient magnetic field drift, and curvature magnetic field drift. It was found that $\mathbf{v}_{\nabla B}$ is the dominant drift in the area between the magnetrons, $\mathbf{v}_E$ is up to ten times smaller in this region, and $\mathbf{v}_R$ can be neglected. In the closed magnetic field configuration, the total drift in the bulk is pointing to the –y direction, causing a pronounced asymmetry of the discharge, as was indeed obvious from Fig. 1. On the other hand, in the case of the mirror configuration, the total drift in the bulk is pointing to the +y direction for the left magnetron area and to the –y direction for the right magnetron area. However, in the mirror configuration, the magnitude of the drift is lower than in the closed configuration, so the particles deflection is less pronounced.

These results not only confirm experimental observations, but also explain the origin of the discharge asymmetry, namely, a combination of electric field drift and gradient magnetic field drift, where the latter is dominant in the area between the two magnetrons.

This work is supported by a joint IWT (SBO 60030) project and a FWO project (G.0027.09) of both research groups. The authors thank Dr. I. Kolev and Dr. P. Baroch for their advice and interesting discussions. The computer facility CalcUA from the University of Antwerp is acknowledged.

[1] V. Kirchhoff, T. Kopte, T. Winkler, M. Schulze, and P. Wiedemuth, Surf. Coat. Technol. **98**, 828 (1998).
[2] M. Saraiva, V. Georgieva, S. Mahieu, K. Van Aeken, A. Bogaerts, and D. Depla, J. Appl. Phys. **107**, 034902 (2010).
[3] V. Georgieva, M. Saraiva, N. Jehanathan, O. I. Lebelev, D. Depla, and A. Bogaerts, J. Phys. D: Appl. Phys. **42**, 065107 (2009).
[4] M. Astrand, T. I. Selinder, and M. E. Sjostrand, Surf. Coat. Technol. **200**, 625 (2005).
[5] J. Musil and P. Baroch, IEEE Trans. Plasma Sci. **33**, 338 (2005).
[6] P. Baroch and J. Musil, IEEE Trans. Plasma Sci. **36**, 1412 (2008).
[7] M. Yusupov, E. Bultinck, D. Depla, and A. Bogaerts, New J. Phys. **13**, 033018 (2011).
[8] E. Bultinck, Ph.D. thesis, University of Antwerp, 2009.
[9] A. Bogaerts, M. Van Straaten, and R. Gijbels, J. Appl. Phys. **77**, 1868 (1995).
[10] E. Bultinck and A. Bogaerts, New J. Phys. **11**, 103010 (2009).
[11] D. A. Frank-Kameneckii, *Lectures on Plasma Physics* (Atomizdat, Moskva, 1964), p. 90 (in Russian).
[12] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Material Processing* (Wiley, New York, 1994), pp. 106–110.