Vacuum 89 (2013) 53–56

Contents lists available at SciVerse ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Estimating electron drift velocities in magnetron discharges

Albert Rauch, André Anders*

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 53, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 31 August 2012
Accepted 1 September 2012

Keywords:
Magnetron
Sputtering
Electron drift velocity

ABSTRACT

Electron motion in magnetron discharges is complicated. In a first approximation, single particle motion can be considered in given electric and magnetic fields to estimate drifts. Based on magnetic and electric field measurements for discharges in an unbalanced magnetron with a strong magnet it is shown that, for the most energetic electrons, the ∇B and curvature drift velocities can be comparable to or even larger than the commonly mentioned $\mathbf{E} \times \mathbf{B}$ drift velocity. In the fluid approximation, the electron pressure gradient adds yet another drift component. Since all of those drifts are generally additive, the term "$\mathbf{E} \times \mathbf{B}$ drift" can be generically used but should be understood to include other drifts. Strong velocity gradients and direction reversal can be found, which suggest velocity shear as a source of waves and instabilities, likely creating the density-fluctuation "seeds" for ionization zones seen in high power impulse magnetron sputtering.

1. Introduction: magnetron operation

Magnetron discharges are widely used in physical vapor deposition. Although a great variety exists in terms of target (cathode) shapes and sizes, they all have in common that energetic electrons are confined near the target by a clever combination of electric and magnetic fields such that energetic electrons execute a closed drift. In this way the magnetron discharge, a magnetically enhanced glow discharge, is enabled to operate at much lower pressure than the common glow discharge, i.e. a glow discharge in the absence of a magnetic field. Much has been published about the magnetron's operational principles and properties [1–12] and therefore it is sufficient to focus here on some relevant details related to the closed electron drifts.

Between collisions, and neglecting collective effects, an electron trajectory is determined by the equation of motion

$$m_e \frac{d\mathbf{v}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (1)$$

where m_e is the electron mass, $\mathbf{v}$ is the velocity vector, e is the elementary charge, and $\mathbf{E}$ and $\mathbf{B}$ are the vectors of the local electric field and magnetic field, respectively. The $\mathbf{v} \times \mathbf{B}$ or Lorentz force term makes electrons gyrate around field lines, and the electric field term causes periodic acceleration and deceleration as the electrons gyrate. In the case when the electric and magnetic fields do not strongly vary one can take the local $\mathbf{E}$ and $\mathbf{B}$ values and arrives at the well-known $\mathbf{E} \times \mathbf{B}$ drift velocity [13,14]

$$\mathbf{v}_{\mathbf{E}\times\mathbf{B}} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}. \quad (2)$$

The magnetic field of a magnetron is designed in such a way that the drift of electrons is closed. The less-energetic electrons, however, are subject to many collisions with other electrons and ions and therefore may not arrive at the same location but are much displaced. Cross-$\mathbf{B}$-field diffusion and a host of plasma instabilities facilitate the escape of electrons from the target zone to the anode. After all, electrons need to carry the discharge current to the anode.

The actual path of electrons in a magnetron is complicated since the electron motion occurs in non-parallel and non-uniform electric and magnetic fields. Powerful three-dimensional codes need to be employed to realistically describe the processes of electron motion in plasmas, including drifts and transport across the magnetic fields [15].

In this contribution, much simplified considerations are made. We will estimate the $\mathbf{E} \times \mathbf{B}$ drift velocity based on measured $\mathbf{E}$ and $\mathbf{B}$ fields, and compare it with other drifts associated with the non-uniformity of the fields. We then also include the electron pressure gradient drift based on plasma parameter estimates.

2. E × B, gradient B, and other drifts

To conceptually understand the drift of electrons in the single particle approximation, one commonly introduces two averaging steps. First, one averages over the gyration motion of the electron to

* Corresponding author. Tel.: +1 510 486 6745; fax: +1 510 486 4374.
E-mail address: aanders@lbl.gov (A. Anders).

0042-207X/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.vacuum.2012.09.002

arrive at the motion of the gyration center. If we neglect for a moment the presence of an electric field, the gyration center would follow the magnetic field line, which is generally arched over the target and intersects the target surface (Fig. 1). As the gyration center approaches the target, the velocity component parallel to the magnetic field line reduces since the magnetic field strength increases (see magnetic mirror effect [13,14]). Now, putting the electric field back in the picture, the electron, before arriving at the target surface, encounters the electric field of the presheath and sheath (the space charge layer adjacent to the target). The electric field component parallel to the magnetic field component sends the gyration center back and forth along the arched magnetic field line. Averaging over this back-and-forth motion reveals a net velocity component which is perpendicular to both the electric and magnetic field. Using characteristic field values one get an estimate for the $\mathbf{E} \times \mathbf{B}$ drift velocity, as described by Equation (2).

This description, however, is not complete since the electric and magnetic fields are not uniform: additional drift components appear. Most notably we deal with a magnetic field that strongly loses strength with increasing distance from the target. A gradient in the magnetic field leads to the $\mathbf{B} \times \nabla B$ and higher order drifts [13]. For electrons (taking the sign of the negative charge of electrons into account), the ∇B drift velocity is [13]

$$v_{\nabla B} = \frac{v_\perp r_L}{2} \frac{\nabla B \times \mathbf{B}}{B^2} \tag{3}$$

where

$$r_L = \frac{v_\perp}{\omega_c} = \frac{m_e}{e} \frac{v_\perp}{B} \tag{4}$$

is the gyration or Larmor radius; ω_c is the gyration or cyclotron frequency, and $v_\perp$ is the velocity of the electron motion perpendicular to the **B**-field. Fig. 2 shows the distribution of Larmor radii assuming the gyrating electrons have $v_\perp$ corresponding to an energy of 10 eV. Electrons of higher energy have a correspondingly greater gyration radius. Here lies one of the difficulties: electrons have different velocities perpendicular to the magnetic field, and the values vary accordingly.

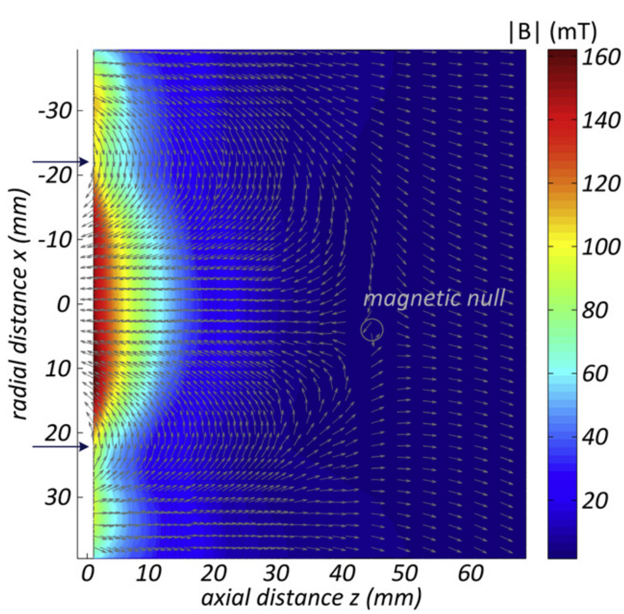

Fig. 1. Measured magnetic field of a 76 mm (3") magnetron with a 6.2 mm (1/4") thick Nb target in place. As evident by the magnetic null point close to the target, this is an unbalanced magnetron (manufacturer US Inc., now MeiVac Inc.). The large arrows on the left indicate the position of the racetrack.

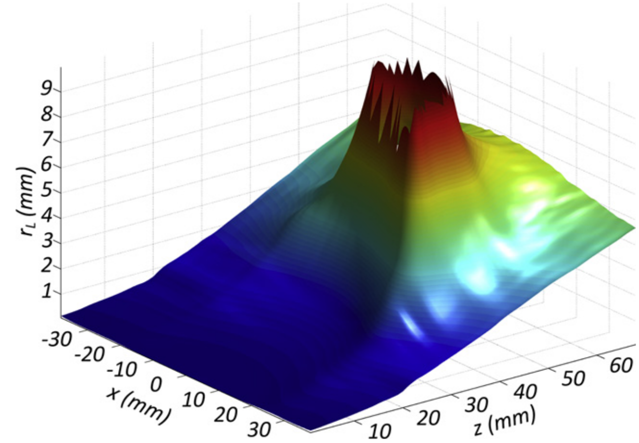

Fig. 2. Electron Larmor radius for the measured magnetic field, arbitrarily assuming a constant velocity perpendicular to the magnetic field vector corresponding to 10 eV. The region around the magnetic null is excluded since electrons are not magnetized when the magnetic field is very weak.

Since we are mostly interested in energetic electrons capable of causing ionizing collisions, we may focus on secondary electrons released from the target by primary ion impact or photo-emission. Such electrons gain energy up to the full potential difference dropping in the sheath, ΔV_{se}, when traversing the sheath. The perpendicular velocity is up to a maximum

$$v_{\perp,\max} = \left(\frac{2e\Delta V_{se}}{m_e}\right)^{1/2} \tag{5}$$

and we arrive at the following expression for the maximum ∇B drift velocity:

$$v_{\nabla B,\max} = \frac{v_{\perp,\max} r_L}{2} \frac{\nabla B \times \mathbf{B}}{B^2} = \Delta V_{se} \frac{\nabla B \times \mathbf{B}}{B^3}. \tag{6}$$

Since ∇B and **E** point in the same direction in the most relevant region over the racetrack, the ∇B drift is generally additive to the $\mathbf{E} \times \mathbf{B}$ drift.

We also consider an expression for the curvature drift [13]

$$v_R = -\frac{m_e}{e} v_\parallel^2 \frac{\mathbf{R_c} \times \mathbf{B}}{\mathbf{R_c}^2 B^2} \tag{7}$$

where $\mathbf{R_c}$ is the radius vector of the curved magnetic field, and $v_\parallel$ is the velocity component parallel to the magnetic field vector.

Going beyond the single particle description by including a fluid model for electrons, electron drift is also caused by the local gradient of electron pressure. In standard text books like [13], the fluid approximation is introduced for electrons and ions, and the resulting gradient drift is called diamagnetic drift. In our case, we do not consider ions because they are not magnetized due to their large mass. They are therefore not subject to such drift, and we prefer the term electron pressure gradient drift. Taking the negative charge of electrons into account, the electron pressure gradient drift velocity is [13]

$$v_{\nabla p} = \frac{\nabla p_e \times \mathbf{B}}{e n_e B^2}. \tag{8}$$

We can write $\nabla p_e = k\,(T_e \nabla n_e + n_e \nabla T_e) \approx kT_e \nabla n_e$ because the density can change by orders of magnitude while the electron temperature varies relatively little. By introducing a characteristic