

Measuring Ion Velocity Distributions and Ion Energy Distributions using Retarding Field Energy Analyzers (RFEAs).

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Setting the Scene

The modification of surfaces through plasma processing is widespread in modern industries. Examples of this include **plasma deposition** of thin films and **plasma etching** of intricate features for integrated circuit manufacture. These processes are heavily influenced by energetic ion bombardment of the work-piece surface. For example, the ion energy distribution impacting a semiconductor wafer surface influences both the etch rate and etch anisotropy.

Ion energy distributions functions (IEDFs), measured with **retarding field energy analyzers** (RFEAs), are often reported in the literature. This 'IEDF' is generally calculated by taking the first derivative (dI/dV) of the ion current (I) versus retarding potential (V) characteristic measured with the RFEA. However, it can be shown that (V) is proportional to the **ion velocity distribution function** (IVDF) and not the IEDF as is sometimes thought.

Now The Math

The ion current density to the surface of the analyser is given by J_i , where n is the ion density e is the electronic charge and v is the average velocity of the ion velocity distribution $f(v)$ arriving at the analyser sampling orifices. The average velocity can be calculated from

$$v = \frac{\int_0^{\infty} v f(v) dv}{n}, \quad (1)$$

where $n = \int_0^{\infty} f(v) dv = \int_0^{\infty} f(E) dE$

Therefore, $J_i = e \int_0^{\infty} v f(v) dv$

and $I_i = Ae \int_0^{\infty} v f(v) dv \quad (2)$

where A is the area of the sampling orifices, I_i is the total positive ion current entering the analyser and $f(E)$ is the ion energy distribution.

By definition, $dn = f(v)dv = f(E)dE$ and therefore $dv = f(E)dE / f(v)$. Since $dE = d(\frac{1}{2}M_i v^2)$ then $dv = dE / M_i v$. Substituting for dv in equation (2) gives

$$I_i = \frac{Ae}{M_i} \int_0^{\infty} f(v) dE = \frac{Ae}{M_i} \int_0^{\infty} f \left[\left(\frac{2E}{M_i} \right)^{1/2} \right] dE \quad (3)$$

The ion current enters the analyser through a sampling orifice(s). A negatively biased mesh, parallel to the orifice plate, repels any incoming electron current back towards the orifice/plasma. A retarding potential applied to a second mesh generates a retarding field for the incoming ions. The retarding field is gradually incremented from 0 eV, which **allows** ions of all energies/velocities to

ions from passing through the mesh. An IV characteristic is constructed by plotting the measured ion current at each retarding potential.

As the retarding potential is increased from $V=0$ to higher positive values, the measured $f(E)$ is reduced due to less energetic ions being repelled by the retarding field. The ion current to the collector can be written as

$$I_i(E) = \frac{Ae}{M_i} \int_E^{E_{\max}} f(v) dE \quad (4)$$

where E_{\max} is the maximum ion energy in the incoming ion energy distribution. Since E_{\max} is independent of the retarding potential, the derivative of (4) becomes

$$\frac{dI_i(E)}{dE} = -\frac{Ae}{M_i} f(v) \quad (5)$$

Substituting the product of the electronic charge e and retarding potential V for the energy E gives

$$\frac{dI_i(V)}{dV} = -\frac{Ae^2}{M_i} f(v) \quad (6)$$

From the discussion following equation (2) it can be seen that $f v = M_i v f(E)$ and therefore

$$\frac{dI_i(V)}{dV} = -Ae^2 v f(E) \quad (7)$$

What Does It All Mean?

It means that dI/dV , which is measured with the [RFEA](#), is proportional to $f(v)$ – the ion velocity distribution. So, a typical RFEA produces a plot of **IVDF versus energy**! What this means in general is that the derivative of the **RFEA ion current versus energy curve** has come to be known as the **IEDF**, which tends to cause some confusion.

To illustrate this, a [RFEA](#) was used to determine the **IVDF** and **IEDF** at the grounded electrode in a rf CCP reactor with an Argon plasma at 2 Pa. The source power was 20 W at 13.56 MHz.

Figure 1 shows the **IVDF** and the **IEDF** determined from equations (6) and (7). For these experimental conditions it is known that there is effectively only one ion species (Ar^+) contributing to the ion current. Therefore, it is straightforward to calculate $f(v)$

conditions it is known that there is effectively only one ion species (Ar^+) contributing to the ion current. Therefore, it is straightforward to calculate $f(v)$ and $f(E)$ because the ion mass is well known. For most plasma processing applications there are many ion species present. In that case it is not trivial to determine the true ion velocity and ion energy distributions. In general, a plot of $f(v)$ versus the ion energy is sufficient and replicates the main features of the true **ion energy distributions**.

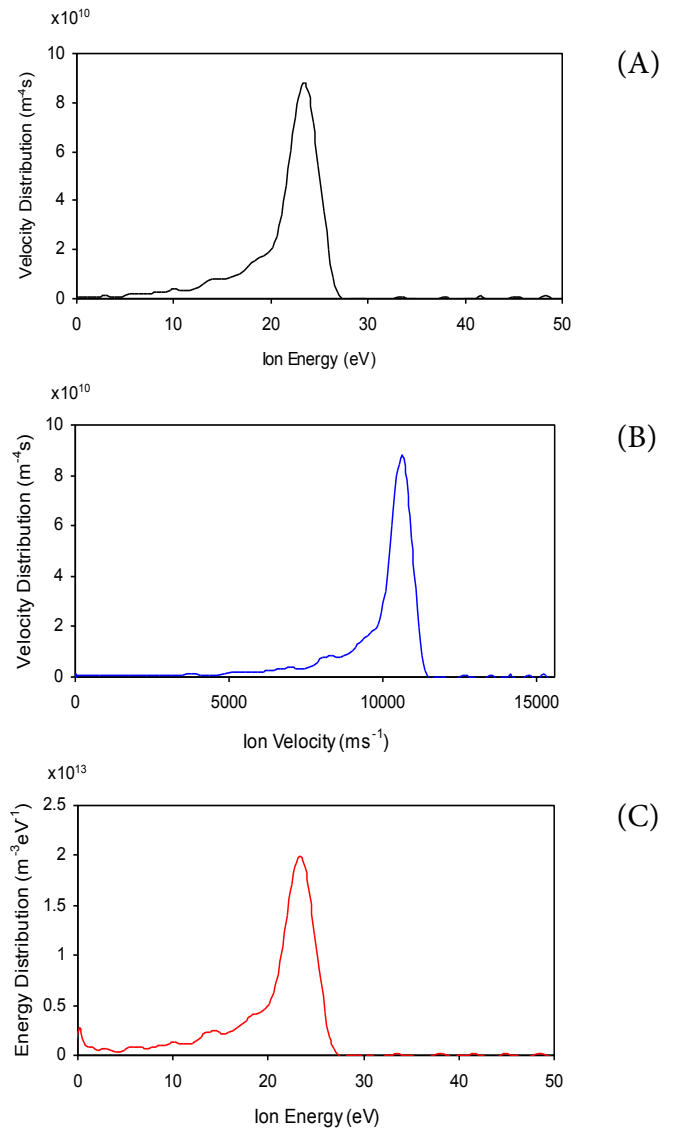


Figure 1: (A) Ion velocity distribution plotted on an energy scale (as produced by a RFEA), (B) Ion velocity distribution plotted on a velocity scale and (C) Ion energy distribution plotted on an energy scale.