ENERGY OF FAST ELECTRONS IN A GAS DISCHARGE AT A PRESSURE OF 10^{-2}-10^{-3} torr

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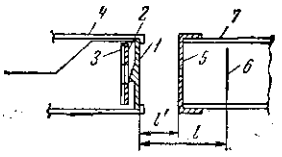

Fig. 1. Arrangement of cathode and collector for measuring the electron energy. 1) Wedge-shaped cathode; 2) Mica-diaphragm; 3) X-ray film; 4, 7) insulating tubes; 5) Outer collector with diaphragm; 6) Inner collector, photographic layer.

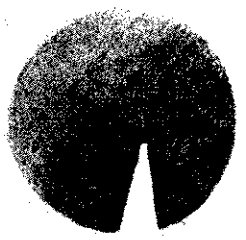

Fig. 2. X-ray patterns obtained by passing the radiation through a wedge-shaped cathode.

We previously reported a study [1] of an anisotropy in cathode sputtering due to the nonuniform current-density distribution over the surface of the sample being sputtered. This nonuniform distribution is consistent with the nonuniform density distribution of fast electrons propagating from the cathode. We report below a determination of the fast-electron energy by two methods; for both methods, the experimental conditions which could affect the experimental accuracy are taken into account.

DETERMINATION OF ELECTRON ENERGY BY REFLECTION IN A UNIFORM MAGNETIC FIELD. This method can be used only when the mean free path λ_e of the electron is greater than the distance l from the cathode to the collector. In this case, an electron moves without collisions over a distance l, and its energy can be calculated from $eU=mv/2$..

The sputtering target, held at a high negative potential with respect to the incandescent plasma cathode, is a copper or aluminum disk 8 mm in diameter under cold-cathode conditions.

The collector is a special chamber (Fig. 1) consisting of outer and inner plates, or electron pickups and the material being sputtered. There is a diaphragm 1 mm in diameter in the outer plate (5). The distance l' from the cathode to the diaphragm and the diaphragm diameter are chosen so that the beam is confined within the diaphragm area with U = 5 kV and H = 100 Oe. Beyond the diaphragm, the beam moves in a charge-free space to the inner collector (6), x-ray film wrapped in black paper. A glass tube (7) protects the electron beam and the photographic layer from the the discharge. The uniform magnetic field is produced by a Helmholtz coil, which is operated briefly (3-4 min) to prevent the field from becoming unstable (due to Joule heating of the coil). The distance l and the displacement of the electron beam ΔS by the magnetic field were determined within 0.1 mm; ΔS was measured at the lower edge of the spot formed on the film, where otherwise an error would enter the energy calculation because of the energy scattering of the electrons.

DETERMINATION OF THE ELECTRON ENERGY FROM X-RAY ABSORPTION SPECTRA. Determination of the electron energy from the x-ray absorption spectra has a wider range of applicability. It can be used in a gas discharge at any pressure, since it involves the determination of the energy of a photon due to an electron which reaches a given cross section of the discharge (at the collector), without an account of collisions with gas atoms and ions as the electron moves toward the collector.

The anisotropy in the x-ray intensity resulting from the anisotropy in the electron-beam density had to be eliminated to prevent errors in the determination of the x-ray absorption coefficient and to allow a more accurate determination of the fast-electron energy. A special cathode was used for this purpose. Two types of wedge-shaped cathode were made from aluminum or copper foil (1 in Fig. 1). As Figure 2 shows, white drips on the photographic film, shielded from the x-rays by a lead wedge (b) and a tungsten wire (a), serve as a blackening reference on the film (i.e., these strips display the blackening background due to the development procedure). The flat side of a foil (Al or Cu) cathode 50 μ thick and 20 mm in diameter is turned toward the discharge to keep the electric field near the cathode surface and thus the current density at this surface more or less uniform. On the other side of the cathode there are strips of the same foil 10 μ thick, bounded by a mica diaphragm 8 mm in diameter or by a slit 2 x 8 mm^2 in size. The x-ray film is placed immediately behind the diaphragm (Fig. 1).

Various glass and metal plates with highly polished surfaces, 20 mm in diameter, are used as collectors; they are placed $\ell' = 10$–15 mm from the cathode in the discharge.

Electrons having relatively low energies, 5-10 keV do not penetrate into the collector material, so white x radiation is excited only from the surface layer of the collector and undergoes essentially no scattering within the collector. Moreover, the x-ray are not scattered in the gas as they move the short distance from the collector to the cathode, so the uniformity of the x-ray intensity is essentially a direct function of the uniformity of the electron density incident on the collector. Since the total cathode area is much greater than the area of the central part, through which the radiation passes, edge effects have essentially no effect on the uniform current-density distribution in the central part of the cathode; accordingly, the x-ray intensity there is uniform. This uniformity is monitored by the passage of x-ray through a cathode oil of uniform thickness. In this manner, the contrast on the x-ray film results primarily from the differences in absorption at different cathode frequencies.

In all cases the absorption coefficient was calculated from photometric data on the linear region of the blackening curve for the film.

EXPERIMENTAL RESULTS. A comparison shows that the fast-electron energy measured by electron deflection in a magnetic field is slightly greater than that determined from the x-ray absorption spectra (Fig. 1). The explanation for this completely plausible difference is that electrons from the complete energy spectrum act on the photographic film in the first case, while in the second the x-ray wavelengths are governed by the maximum of the intensity curve. The wavelength at the maximum is 1.5 times the minimum wavelength at the edge of the $J=f(\lambda)$ curve [2]. Introducing a correction as we determine the electron energy for the λ minimum, we find an energy equal to that determined by the magnetic-field deflection. For accelerating voltages U = 5, 7 and 9 keV between the cathode and anode, the electron energies measured are 9, 12 and 16 keV (maximum values). One cause of the increase in the electron energy may be the predominant Joule ionization of atoms having the greatest charge. Since we have $\lambda_e \gg l$ for $p = 10^{-2}$–10^{-3} torr, electrons do not cause ionization. Though ionization is caused by x-rays formed as electrons from the cathode beam are stopped in the collector. Ionization of atoms by the x-rays produces photoelectrons and photo ions. With sufficiently short x-ray wavelengths, the photon energy becomes sufficient to remove electrons bound more tightly, and this removal occurs especially frequently under these conditions (90% of the cases). The kinetic energy of the photo electrons is $E = h\nu - E_g$, where E_g is the energy of the atomic level from which the electron is removed. Since the electron arises in an electrostatic field, its total energy is $E_t = h\nu - E_g + E_{acc}$. For example, for the case of photon absorption by Cu atoms under the conditions $U_{acc} = 5000$ V, we have $E_t = 5000 - 951 + 5000$ eV, i.e., $E_t = 9049$ eV, nearly equal to the experimental electron energy of $E_e = 9240$ eV.

A photo ion produced in this manner is unstable. Photoionization in a gaseous medium is a complicated process; most of the fast electrons may be, instead of primary photoelectrons, secondary or tertiary Auger electrons. Accordingly, we would not find the experimental electron energy to be exactly equal to that calculated from Eq. (1).

It was found experimentally that the ionized atoms of the sputtered material follow the electron beam; becoming adsorbed on the inner collector, they form a film only where the electron beam strikes. From the experimental data we calculated the energy of these Cu photo ions to be $E_I = 0.07$ eV (where $u_{acc} = 5000$ V $\ell = 2$ cm).

The author thanks Professor V. I. Iveronova for discussion of these results.

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