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BRIEF COMMUNICATION

Use of secondary-electron yields determined from breakdown data in cathode-fall models for Ar

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Abstract. We test the utility of recently published secondary-electron yields per ion for the prediction of operating voltages for abnormal cathode-fall discharges in Ar for normalized current densities $\leqslant$20 mA cm^{-2} Torr^{-2}. The effective secondary-electron yields per ion derived from spatially-uniform field breakdown and low-current discharge data give much too small discharge voltages at the higher current densities. In contrast, published secondary-electron yields per ion derived from ion-beam data at high ion energies and brakdown data at low ion energies give abnormal cathode-fall voltages that are within the present uncertainty of the models and of experimental data for Cu cathodes.

In this communication we examine whether recently published [1]† effective electron yields per ion γ_{eff} or actual electron yields per ion γ_i, are useful for modelling the cathode fall of abnormal glow discharges in Ar at low and moderate current densities [2–6]. These questions were left unanswered by a recent review in this journal on the various processes responsible for the production of secondary or avalanche-initiating electrons for uniform-field breakdown or very-low-current discharges [1]. Because γ_{eff} includes the contributions of all secondary-electron processes of importance for uniform-field breakdown conditions, there is a strong temptation to use the γ_{eff} values in models of the cathode fall. Section 3 of [1] includes a detailed discussion of the variety of electrode surface conditions encountered in the determinations of electron yields per ion from breakdown and beam data. It also addresses the question of changes in electron yields caused by discharge sputtering, electrode heating, etc. In the present analysis we assume that the electron yields are not changed by the discharge.

The γ_{eff} values used in this analysis are taken from the full curve of figure 11 of [1] and are reproduced in figure 1. The γ_i values used are taken from equation (B8) and the corrected equation (B16) of [1] and are shown by the lower curve in figure 1. The reader is referred to [1] for the details of the determination of these values from the uniform-field breakdown, low-current discharge, and ion-beam data. In

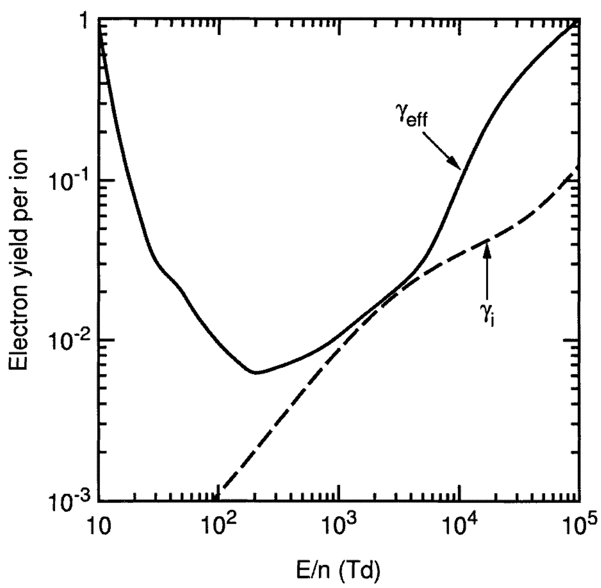

Figure 1. Electron yields per ion against E/n as determined from uniform-field breakdown voltages, low-current discharge voltages and ion-beam experiments. The effective electron yields γ_{eff} and the recommended true γ_i are from [1].

figure 2 our calculations of discharge maintenance voltages are compared with experimental data for Cu cathodes [5, 7, 8] for a wide range of the scaled current density j/p^2 and for $pd \geqslant 0.5$ Torr cm. Here j is the discharge current density, p is the pressure, and d is the separation of the parallel-plane electrodes. We have omitted the experimental data of Klyarfel'd *et al* [9], where the Cu cathodes were

† The corrected right-hand side of equation (B15) is $\{0.006\epsilon_i/[1 + (\epsilon_i/10)]\} + \{1.05 \times 10^{-4}(\epsilon_i - 80)^{1.2}/[1 + (\epsilon_i/8000)]^{1.5}\}$. The corrected right-hand side of equation (B16) is $\{0.06[kT_+ - 10\exp(10/kT_+)\Gamma(0, 10/kT_+)]/kT_+\} + 10^{-4}(kT_+)^{1.2}\exp(-80/kT_+)[1 + (kT_+/6000)]^{1.5}$.

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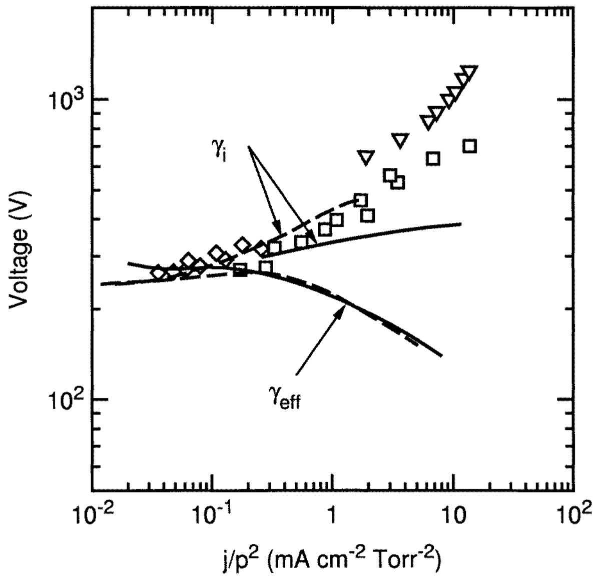

Figure 2. Comparison of calculated and experimental discharge voltages for abnormal cathode-fall discharges in Ar. The full and broken curves show the results of the hybrid models of [10] and [11], respectively. The symbols and references for the experimental data are: ▽, quoted in [5]; □, [7]; and ◇, [8]. We have omitted the much lower voltage measurements from [9].

treated by heavy sputtering and the cathode-fall voltages are significantly lower than those shown.

The lower full [10] and broken [11] curves (labelled γ_{eff}) of figure 2 show discharge voltages calculated using hybrid models of the abnormal cathode fall in Ar and the γ_{eff} values of figure 1 for electron production at the cathode by Ar^+. These hybrid models use Monte Carlo techniques for the high-energy electrons and local-field fluid models for the low-energy electrons and ions [4]. The models are one-dimensional and so do not predict the radial constrictions expected in the vicinity of our lowest current densities [2] or the effects of the radial losses expected in narrow discharge tubes. The γ_{eff} is determined by the electric field to gas density ratio at the cathode $(E/n)_c$ and only secondary-electron production by Ar^+ is included. These calculations are for relatively large *pd* values, i.e. 1.5 Torr cm, so that we can neglect the backscattered or secondary electrons from the anode. The relatively small differences between the calculated curves appear to result from different fits to the electron yield data, numerical procedures, etc. The large decrease in the calculated voltage with j/p^2, i.e. the large negative slope of the calculated voltage–current curve, is in strong contrast to the increase in voltage with increasing current found experimentally. We therefore conclude that the γ_{eff} derived from the uniform electric field data and including all secondary-electron production processes should not be used with the non-uniform electric field models appropriate to cathode-fall discharges at the higher values of j/p^2.

The decrease in the calculated discharge voltages results from the rapid increase in γ_{eff} for $(E/n)_c > 6$ kTd corresponding to $j/p^2 > 0.2$ mA cm^{-2} Torr^{-2}. Here 1 Td $= 10^{17}$ V cm^2. In section 5.3.2 of [1], this increase in γ_{eff} is shown to arise primarily from ionization of Ar by fast Ar and Ar^+ under uniform electric field conditions. In order to understand the apparent lower efficiency of heavy particles in the ionization of Ar atoms and in electron production at the cathode in the presence of the highly localized electric field of the cathode fall, it is important to examine more detailed models, for example Monte Carlo calculations [5, 6, 12]. For example, these Monte Carlo calculations show that at high j/p^2 the fast Ar atom mean-free-paths are comparable with the cathode-fall thickness so that much of the Ar atom energy is lost to the cathode. However, direct comparisons of the uniform-field and non-uniform-field results have yet to be published.

At $j/p^2 < 0.2$ mA cm^{-2} Torr^{-2} in figure 2, discharge voltages calculated using the γ_{eff} of figure 1 are in satisfactory agreement with the scattered voltage data. We note that for this range of j/p^2 and $(E/n)_c$ one expects ion-induced electron emission at the cathode to be the dominant secondary-electron source under breakdown conditions [1]. We therefore examine whether γ_i is useful for predicting discharge voltages at the higher j/p^2. The upper pair of curves, labelled γ_i, are calculated using the γ_i values of figure 1 for a *pd* of 1.5 Torr cm. These voltages are in much better agreement with experiment than the voltages calculated using γ_{eff}. Because the limited j/p^2 and *pd* of our present models, we leave open the possibility that under some circumstances electron production by fast atoms in collision with gas atoms and with the cathode is important in the abnormal cathode-fall discharge. This question and the effects of changes in *pd* and the tube radius on the discharge characteristics are currently being examined.

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