Preflashover phenomena and electron-stimulated desorption in high electric fields*

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(Received 24 September 1973)

The effect of high electric fields on the electron-stimulated desorption (ESD) of positive ions from metal surfaces has been studied at fields between 10^3 and 10^5 V/cm for electron energies between 1 and 20 kV. Adsorbed gases characteristic of the residual vacuum (10^{-9} Torr) were detected under all conditions, but ions characteristic of the substrate were only detected for fields approaching 10^5 V/cm. These observations confirm that previously reported *preflashover* anode metal ion species in an ultrahigh-vacuum diode originate at anode protrusions by a field evaporation process and that only residual gas species are produced prior to flashover by ESD. It is suggested that, if field emission processes at the cathode could be completely suppressed, electrical flashover would still occur, initiated and sustained by field-evaporated anode ions.

A recent examination of preflashover anode ion species in a planar ultrahigh-vacuum diode[1] has suggested that electrons, field emitted from microscopic cathode protrusions, desorb species from the anode surface as positive ions. Some of the observed ions are highly charged and characteristic of bulk anode material, a surprising result since previous electron-stimulated desorption (ESD) experiments[2,3] have not reported species characteristic of the substrate under investigation. However, these ESD experiments have been performed with small external fields at the specimen surface ($< 10^3$ V/cm) and with bombarding electron energies limited to a few kilovolts, conditions quite different than those encountered during preflashover studies.

In order to determine the effect of the large electric field present during a flashover experiment[1] on ESD anode ion production, we have constructed a time-of-flight electron desorption spectrometer and present in this paper the first observation of ion species originating at clean metal surfaces when bombarded with electrons having tens of kilovolts of energy at fields up to 10^5 V/cm.

The apparatus is shown in Fig. 1. Electrons are produced by either a field emission or dispenser cathode[4] source. A current density of $1\mu A/cm^2$ was established at the sample for electron energies from 1 to 20 kV. The diameter and uniformity of the impinging electron beam was observed by means of a phosphor screen which was placed in one sample position on the specimen carrousel. The carrousel permitted five different polycrystalline specimens to be examined without breaking the vacuum. These included aluminum (2*s* alloy), magnesium, copper, tungsten, and niobium. Provision was made for thoroughly degassing each specimen by electron bombardment from a small filament. During operation of the electron gun, the background vacuum never exceeded 8×10^{-9} Torr.

The cathode of the electron gun was pulsed negatively with a high voltage pulse of amplitude $-V_c$, a rise time of 10 nsec, and a duration of 50 nsec, which resulted in an electron energy at the sample of

$$E_e = e(V_c + V_A),$$

where V_A, applied directly of the sample, determined the kinetic energy of ions formed at its surface. Since V_A also determined the magnitude of the electric field at the sample surface, it was adjusted first to provide the desired field strength between 10^3 and 10^5 V/cm. Then V_c was adjusted so that the total electron energy would be between 1 and 20 kV. The experiment consisted of observing the ion species from each sample for several electron energies between 1 and 20 kV at fields of 10^3, 10^4, and 10^5 V/cm. Electrical flashover[5] frequently occurred for fields greater than 10^4 V/cm at electron energies above 10 kV. Ions produced during such events were disregarded.

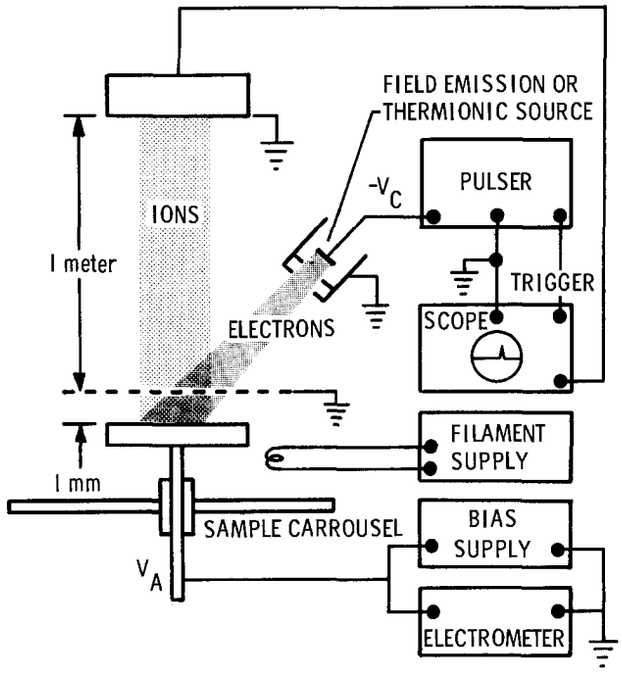

FIG. 1. ESD spectrometer. Bias voltage V_A determines ion kinetic energy as well as the field at the sample surface. By rotating the sample carrousel, each of four specimens can be examined. The fifth specimen position contained a phosphor screen to determine visually electron beam area and uniformity. The electrometer permits measurement of beam current when operated at a dc potential equal to the pulse amplitude applied during actual operation. In this experiment a current density of $1\ \mu A/cm^2$ was maintained to approximate the field electron emission current density occurring prior to visible flashover in an ultrahigh-vacuum diode. Only ions produced by the ESD process are shown.

TABLE I. Substrate ion species observed at fields approaching 10^5 V/cm for all electron energies investigated (residual gas species not shown). For fields below 10^4 V/cm only residual gas species are observed. The abundance of species from the magnesium sample always appeared to be at least a factor of 2 larger than those observed from the other samples.

Sample	Species
Al [a]	Cu^+, Al^{2+}, $Al_2O_3^{3+}$, Mg^+
Mg	Mg^+, MgO^{2+}
Nb	Nb^{2+}
W	W^{3+}

[a] 2*s* aluminum alloy (Al, Cu, Mg).

In order to identify the positive ions formed during each pulse of the electron gun, an oscilloscope was connected to the output of an electron multiplier positioned 1 m from the sample. Since the sweep of the oscilloscope was triggered by the pulse applied to the electron gun, the travel time of each ion species detected by the electron multiplier could be accurately measured. Because an ion drifts with constant velocity between sample and detector, its observed travel time T is just

$$T = d/v,$$

where v is the drift velocity and d is the 1-m drift distance. At the entrance to the drift region, an ion of mass m and charge q has a kinetic energy given by

$$\tfrac{1}{2}mv^2 = qV_A = neV_A,$$

where n is some integral multiple of the electron charge e so that its mass-to-charge ratio in amu is

$$m/n = (0.193/d^2)V_A T^2,$$

where V_A is in kilovolts, T is in microseconds, and d is in meters. Since some residual gas ion species are expected to be produced by electron bombardment along the electron beam trajectory from grid to sample, it was necessary to uniquely identify those ions originating at the sample surface. This was accomplished by changing the sample bias V_A by a few hundred volts, ΔV_A, and noting the shift in travel time, ΔT, for the ion species displayed on the oscilloscope. Only those ions originating at the sample surface would have their time shifted by the unique amount

$$\Delta T = \frac{1}{2}\left(\frac{m/n}{0.193}\right)^{1/2} d\frac{\Delta V_A}{V_A^{3/2}}$$

and therefore could be easily identified.

The experimental results clearly showed that, for all combinations of applied field and electron energies, ions characteristic of residual gas species adsorbed on the surface were produced. Comparison with the mass spectra obtained from an attached quadrupole confirmed this observation.

For fields approaching 10^5 V/cm, the species shown in Table I, characteristic of the substrate, were detected *in addition* to adsorbed gases. Since the appearance of these metal anode species was definitely related to the magnitude of the field at the anode surface and not to the electron kinetic energy, we believe that they originate at microscopic anode protrusions[6] and that they are produced by a field evaporation process. The total number of such ions detected in the absence of visible flashover was too small to produce an observable deposit on the electrode opposite the anode (cathode). However, during a flashover event a drastic increase in anode ion abundance must take place, since a coating of anode material is usually observed. This in turn implies that either the field evaporation process producing preflashover metal anode species increases enormously during flashover[7] or another effect becomes dominant.

Consider the temperature rise of an anode whisker 10^{-4} cm in length, due to preflashover bombardment by 20-kV electrons from the cathode at a current density of 1 μA/cm^2. By assuming an aluminum whisker and an electron pulse duration of 50 nsec, the temperature increase of the whisker will be negligible. However, if the current density approaches a few hundred A/cm^2, as does occur at flashover, the whisker temperature will increase beyond its melting point and will produce molten anode material which can subsequently ionize,[8] travel to the cathode, and produce a visible deposit. This appears to be the dominant mechanism for producing gap conduction by positive ions *at flashover*. However, prior to flashover, when the field-emitted electron current density is only μA/cm^2, field evaporation and desorption will dominate anode ion production. If one could suppress all electron emission at the cathode, such anode processes would be expected to initiate and control gap conduction.

It is worthwhile at this point to distinguish between small-gap and large-gap flashover. Since preflashover phenomena are definitely field dependent, we suggest that the formative mechanisms leading to flashover will be qualitatively independent of gap spacing. However, the quantitative nature of the phenomena should depend critically on electrode separation, since a large gap requires a large potential difference to establish a given field strength. As a result, the final kinetic energy of electrons striking the anode surface will increase with increasing interelectrode spacing, and therefore the abundance of anode ions produced by anode melting or thermally enhanced field evaporation will increase.

Finally, we wish to point out that, because the initiation mechanisms for breakdown appear to be critically dependent on electrode surface properties,[9,10] it is essential to perform such experiments under controlled clean ultrahigh-vacuum conditions. This is important not only for cathode investigations, where work function changes can drastically affect electron emission properties, but also for anode investigations, where adsorbed contaminants will affect the ease of ion production and the nature of the resulting species.

*Supported by the U.S. Atomic Energy Commission.

[1] J.A. Panitz, J. Appl. Phys. 44, 372 (1973).
[2] T.E. Madey and J.T. Yates, Jr., J. Vac. Sci. Technol. 8, 525 (1971).
[3] I. Newsham, J.V. Hogue, and D. Sandstrom, J. Vac. Sci. Technol. 9, 596 (1972).

[4]Spectra-Mat, Inc., Watsonville, Calif., No. Std. 500.
[5]"Electrical flashover" is defined for the purpose of this letter as the appearance of a highly localized visible spark between anode (substrate) and grid, since no satisfactory definition of "breakdown" appears in the literature. The advantage of this definition is that, at least in principle, it is independent of instrument parameters such as power supply impedance and can be defined empirically and directly in terms of a given number of photons. If the photon wavelength is specified, the definition becomes dependent on the electrode material used but still remains independent of instrument parameters.
[6]J.A. Panitz, 1972 *Annual Report, Conference on Electrical Insulation and Dielectric Phenomena* (National Academy of Sciences, Washington, D.C., 1973), p. 113.
[7]It is well known that field ion microscope tips, analogous to anode protrusions, exhibit marked instabilities when the field approaches some critical value [T.J. Wilkes, J.M. Titchmarsh, G.D.W. Smith, D.A. Smith, R.F. Morris, Suzanne Johnston, T.J. Godfrey, and Penny Birdseye, J. Phys. D 5, 2226 (1972)]. Such a "tip jump", which produces a catastrophic increase in ion production at or near the whisker surface, may contribute to gap conduction.
[8]D.K. Davies and M.A. Biondi, J. Appl. Phys. 41, 88 (1970). Unlike these authors, our results always indicate that ionization of anode species occurs at the anode surface and *not* in the gap between anode and cathode.
[9]J.J. Maley, J. Vac. Sci. Technol. 8, 697 (1971).
[10]D.W. Williams and W.T. Williams, J. Phys. D 5, 1845 (1972).