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TECHNIQUES FOR THE STUDY OF BREAKDOWN BETWEEN LARGE AREA ELECTRODES IN VACUUM

by

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SUMMARY

From experiments dealing with electrical breakdown phenomena in vacuum, it is clear that at voltages below that level actually required to produce breakdown, there occurs a low-level electron emission from highly localized regions of the cathode surface. This report illustrates a technique for measuring the dependence of current upon voltage from one such region utilizing variations in brightness of a phosphor screen. The technique avoids the possible confusion of a total current measurement which can result from the presence of simultaneously emitting areas or which can result from emission from regions of the electrode structure whose contribution to total current is unsuspected.

This report further demonstrates a method for the detailed location of particular emitting areas on the electrode surface. The procedure involves as a first step, the determination of the approximate location of the emitting region of interest using a phosphor screen. Following this, the electrode under study is used as a cathode opposite a lead anode without breakdown. This serves to evaporate lead metal from the anode surface areas lying directly opposite the cathode emitters. Charged vapor from the anode moves toward the cathode under the influence of the applied field and is deposited in the immediate region of the emitter. Subsequently, this lead can be detected in the scanning electron microscope using microprobe x-ray analysis. This serves to identify the emission region.

KEY WORDS

vacuum breakdown, field emission,
vacuum switch

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TECHNIQUES FOR THE STUDY OF BREAKDOWN BETWEEN LARGE AREA ELECTRODES IN VACUUM

G.A. Farrall and M. Owens

INTRODUCTION

From numerous studies of breakdown in vacuum, it is clear that in many instances the ability of a device to withstand high voltage without breakdown is determined by microscopic or submicroscopic regions located at random on the surface. At voltages below the level actually required to produce breakdown, these regions located at the cathode produce electron emission which becomes greater at higher voltage. Excessive emission at a critical voltage is felt by many to actually initiate breakdown. It is clear that in cases where the experimental device has been carefully cleaned and rigorously outgassed, the emission areas are actually metallic projections which act to enhance the average electric field by a factor in the neighborhood of 100.(1, 2) The observed electron emission is easily accounted for in such cases by field emission at the highly stressed tip of the projection.

In some cases, however, the precise nature of these critical electrode regions is not known. Yet the assumption is often made that the conditions for simple field emission from metallic projections prevail. This conclusion is based upon the observation that the dependence of prebreakdown emission follows the Fowler-Nordheim equation and that the field enhancement factor determined from a linear Fowler-Nordheim plot is not higher than a few hundred. Despite the fact that these criteria may appear plausible, they still constitute assumptions. This report suggests experimental techniques which will lead to more complete information concerning these very critical regions of the electrode surface.

The techniques employed depend upon the use of phosphor screen diode devices which serve to project the electron emission from the cathode surface upon a phosphor screen anode under conditions such that the projected magnification is low or even unity. This technique has been used effectively by several investigators; see examples by Brodie,(3) Little and Whitney,(4) and Utsumi (Ref. 5). We have ourselves previously reported the use of such devices to correlate the location of emitting areas with actual sites of breakdown (Ref. 6).

Two particular applications of this technique will be discussed: the determination of the dependence of emission current from a local emitting region upon voltage, and the use of phosphor screens as a part of a general technique for precise location of electron emitting regions on the cathode.

MEASUREMENT OF EMISSION FROM A SINGLE SITE

If one considers the total prebreakdown current produced by a large collection of randomly chosen emitters, it is likely that the emission will be dominated by the one emitting area most sensitive to the electric field.(7, 8) In such a case a measurement of the total prebreakdown current through the device as a function of voltage will truly reflect the characteristics of that single emitter.

It is possible, however, that current will arise from an unexpected source such as the electrode support structure or that a statistically improbable combination of emitters will produce significant current from more than one region. In any event, it is experimentally much more satisfying to know that the measured current is emitted from a known region of the electrode. Slivkov(9) has devised an apparatus for determining the current from discrete regions of a large area cathode utilizing a segmented anode incorporating individual current monitoring for each segment. This section of the report describes an alternative technique.

The brightness of a phosphor depends markedly upon the current density of the beam striking the phosphor and the energy of the impacting electrons. In general, the response of a phosphor is close to linear with current density except at the extremes of very low current density and extremely high current densities where saturation effects become important.(10) In principle, then, once the dependence of brightness upon electron energy is known, the relationship between brightness and voltage applied across the diode can be reduced to yield the relationship between current arriving at the phosphor and the applied voltage.

The electron energy response to a phosphor will depend upon the type of phosphor used and its preparation so that, in general, this response must be determined individually. In the present work two methods were used to study the voltage effect. The first utilized a triode structure in which a grid was used to establish field emission at a cathode surface. The anode potential could be separately varied to establish electron energies. A second method employed an electron gun as an emission source permitting continuous change in beam current and focus. Both methods gave comparable results.

Three separate diode tubes were made to test the method using electrodes of polished copper, molybdenum, and Vascomax,(11) respectively. The emission for each of these devices was widely different. In each case the dependence of total current upon voltage as determined by direct measurement and that deduced from phosphor screen measurements was compared. Maximum differences of about 30% were found. This error is, however, more attributable to the fluctuating levels in current in the device being studied than to the accuracy of the method itself.

Figure 1 illustrates the application of this technique. Shown in the photograph is a view of the phosphor screen diode face (6.35 cm in diameter). The phosphor layer is semitransparent so that the molybdenum electrode surface is visible. The electrode is mushroom-shaped but has a flattened face. Six prominent emitters on the screen are identified by number in the diagram above. During measurements the entire face of the tube was masked with black paper except for a single emitter location which was viewed through the mask by means of an aperture of fixed diameter. The light intensity variations as a function of voltage across the tube were studied in this way for each emitter or emitter complex visible on the screen. Two experimental runs were recorded for each emitter: one with the aperture viewing an emitter, and the second with the aperture viewing an area adjacent to, but not including, a given emitter. The actual data point was taken as the difference between these two numbers. The reason for this procedure is that the electrode surfaces are all polished and the phosphor screen is semitransparent. Light from the phosphor screen produced by one or more emitters is reflected from the electrode surface and detected by the photomultiplier. This effect, incidentally, is illustrated in Fig. 1 by the spot on the photograph representing emitter No. 1. While there appear to be two emitting areas at 1, the less bright image is, in fact, a reflection from the electrode surface. Figure 2 shows the relative current from each emitter as a function of voltage. Only drawn curves have been illustrated to avoid the confusion of data points.

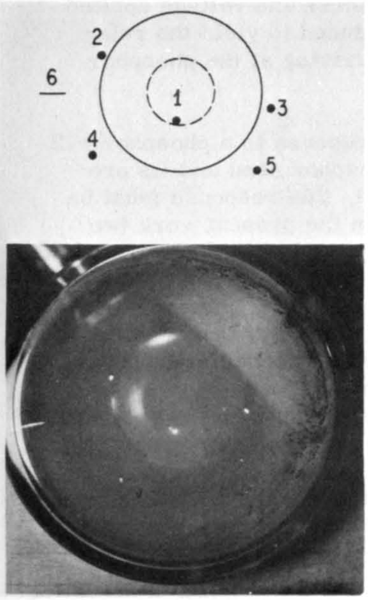

Fig. 1 Phosphor screen pattern with reference numbers for six prominent emitters.

A further advantage to the use of phosphor screens accrues from the fast transient response of certain phosphors. The measurement of field emission currents on devices subjected to time-varying voltages has always been difficult because of the presence of unavoidable displacement current. The use of a phosphor screen thus offers the promise of a relatively simple way of following time varying emission currents, since it responds to electrons traversing the gap and is insensitive to displacement current.

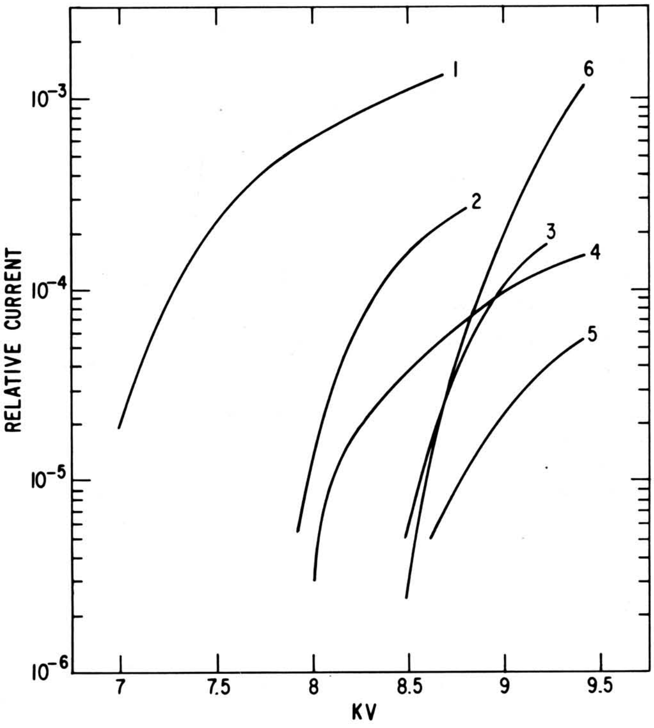

Fig. 2 The dependence of current upon voltage for the six emitting regions of Fig. 1.

To illustrate this technique, the molybdenum phosphor diode tube was subjected to a 60-cycle, half-wave rectified high-voltage wave form and phosphor brightness variations followed with a photomultiplier. The high-voltage wave is shown as the lower trace of Fig. 3 at 2 kV/div. Photomultiplier output is shown as the upper trace with increase brightness giving a downward deflection. This oscillogram is a time exposure of 4 seconds with voltage continuously applied so that approximately 240 individual traces are superimposed.

In connection with this figure, two points should

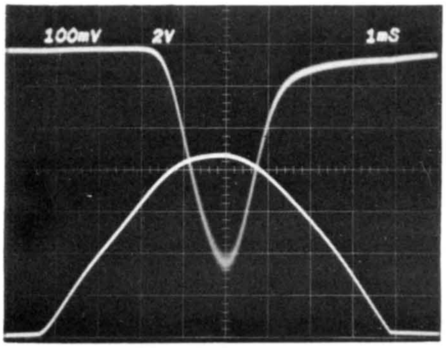

Fig. 3 Brightness variation of phosphor due to field emission produced by half-wave rectified high voltage.

be emphasized. The first is that the brightness trace is nonsymmetrical. This is due to the finite phosphor decay time so that the meaningful part of this trace is the leading edge. The second point is that brightness itself is not directly proportional to current since the brightness component due to electron energies striking the screen must be taken into account. The method does, however, permit inference of current magnitude from the oscilloscope trace.

EMISSION SITE LOCATION PROCEDURE

In the foregoing section, simple diode structures having conventional phosphor screens were used to study the emission from microscopic regions of the cathode surface. Since the phosphors were particulate, the cathode surface could become contaminated via particle transfer from the screen. We wished to avoid this possibility. Our interests were further directed toward an experimental procedure which would enable us to photograph, under high magnification, the emitting regions of the cathode. The adopted method utilized five important components: (1) a vapor reacted phosphor screen which is a continuous film and mechanically stable; (2) a gridded cathode electrode which when used in conjunction with the phosphor screen would provide approximate location of emission areas; (3) a lead anode screen; (4) the scanning electron microscope; and (5) a solid-state x-ray detector for electron microprobe analysis.

The gridded electrodes were disks of zone-refined copper 1.2 cm in diameter and 0.95 cm high. These dimensions were governed by the sample chamber of the scanning electron microscope. A matrix of lines with 0.066 cm spacing was etched into the surface of the copper electrode by means of presently available printed circuit board technologies. A triangular keyway in the pattern provided a reference mark. The electrode after gridding and electropolishing(12) was immediately placed in a vacuum system and a pressure of $\sim 10^{-6}$ torr attained. See Fig. 4.

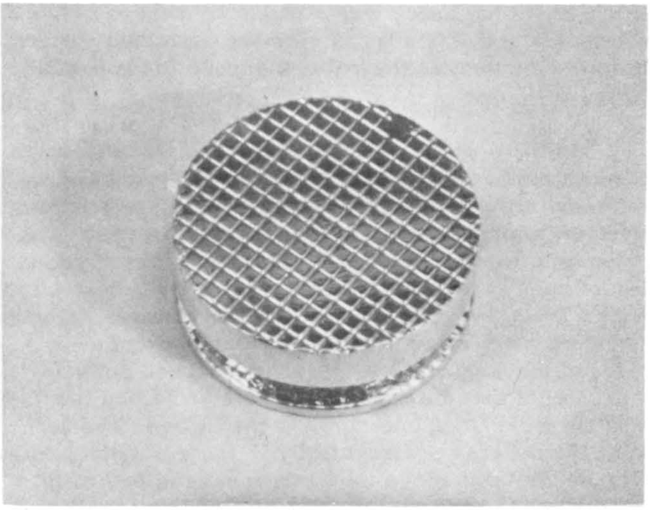

Fig. 4 Copper electrode with etched surface grid.

The tube in which part of this study was conducted (Fig. 5), was assembled using copper gaskets so that the electrode could be easily changed. The anode of the system consisted of three 3.2-cm-diameter screens on a rotatable mechanical feedthrough, which allowed each anode screen, in turn, to be used opposite the cathode. In all cases the electrode to anode gap was set at a value between 0.025 and 0.1 cm as measured by an optical microscope (80X) at the point of emission.

The first of the anode screens was a tungsten wire mesh which was used to partially condition the electrodes to achieve a more stable emission pattern from the surface.

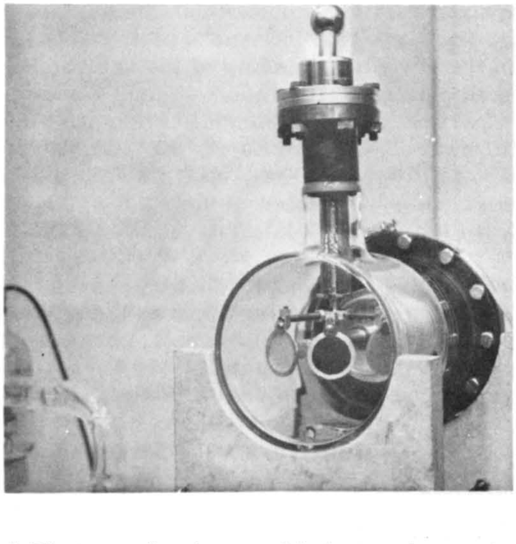

Fig. 5 Photograph of assembled experimental tube.

The second anode was a phosphor screen (vapor reacted) which was used to view the emission pattern from the surface as the voltage across the gap was varied.

The third anode of the system was a lead film on a Pyrex disk, the purpose of which was to mark the emission sites for later identification in the scanning electron microscope. This "marking" process appears to involve the vaporization and partial ionization of anode metal by the incoming flux of electron beams from the emitting areas of the cathode. Anode metal may be removed either atomically or as charged macroparticles.(13) The charged components would thus be expected to proceed along the electric field lines back toward the cathode and deposit themselves preferentially in the emission areas. Such deposits of anode metal on local regions of the cathode were observed in 1931 by Bennett.(14) Lead was chosen as an anode material because its high vapor pressure and high atomic number should enhance the probability of detection at the cathode. The electrode surfaces were exposed to lead deposition for 10 to 15 minutes. The voltage across the gap at the time of anode metal transfer was in the middle of the range used for the emission current measurements. If at any time during the lead coating cycle an arc occurred, the experiment was terminated and a new electrode prepared. A higher voltage was required to observe the same apparent brightness on the phosphor screen after lead coating than before. This was very likely due to the deposits of lead near the emitter.

The electrode was then placed into the sample chamber of the scanning electron microscrope. By using a photograph of the emission location superimposed upon the electrode grid, the area of emission could be located to within a 10-mil-square area. Each possible site in the emission area was sampled for the presence of lead using a solid-state x-ray detector(15) in conjunction with the SEM. An emission site located in this way (Fig. 6) appeared to be a micron-sized particle embedded in the surface of the electrode near a grid line and was probably left over from the abrasive finishing of the surface before the grid pattern was etched. Figure 7 shows this same particle at a high magnification and viewed from a different angle. Points #1, #2, and #3 were subjected to microprobe x-ray analysis with the result for #1 and #2 indicated at the right of Fig. 7. The analysis for #3 was similar to that for #1 and #2.

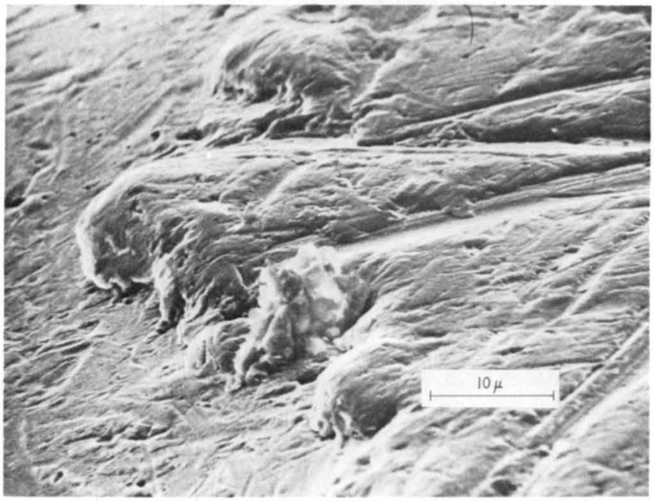

Fig. 6 Particle in copper electrode surface. Particle width is about 6μ.

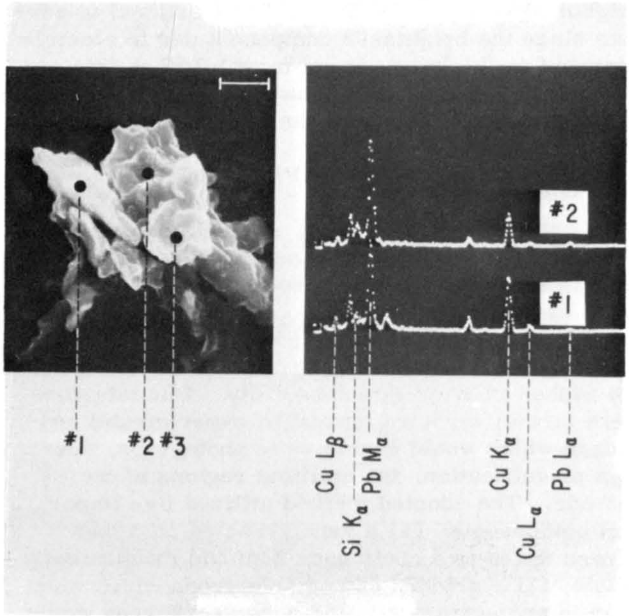

Fig. 7 Same 6μ particle in Fig. 6 showing the three regions sampled for x-ray microprobe analysis. At right is the analysis for regions 1 and 2. Scale bar is 2μ.

Samplings #1, #2, and #3 showed high concentration of lead, while samplings next to the particle showed none. Other materials were identified in the particle. While copper responses were expected, silicon could have only been part of the makeup of the particle. The presence of silicon suggests that the emitter complex is an insulating particle imbedded in the copper surface. Aluminum was also detected and could have come either from the aluminum coating on the phosphor anode or from a particle of Al_2O_3. Future work will, therefore, avoid the use of aluminum on the phosphor. The question of the origin of aluminum might have been resolved by the presence of oxygen, but the x-ray detector was insensitive to elements with atomic number below that of fluorine. Samplings of many particles in the area showed no lead.

During the use of this electrode opposite the phosphor screen, measurements were made of the dependence of current upon voltage from the particular site shown in Figs. 6 and 7. These data are given in Fig. 8 in both linear and Fowler-Nordheim forms. The slope of the Fowler-Nordheim plot yields a field enhancement factor of 230.

Experiments with a different cathode surface using the same procedures revealed the structures shown in Fig. 9. Aluminum (in addition to lead) was identified as a constituent of the emitter. The structure shown is part of a complex of emitters extending in a line over a distance of about 1/2 a grid length on the electrode. The Fowler-Nordheim plot of the emission from the whole complex is given in Fig. 10 and yields a calculated enhancement factor of 226.

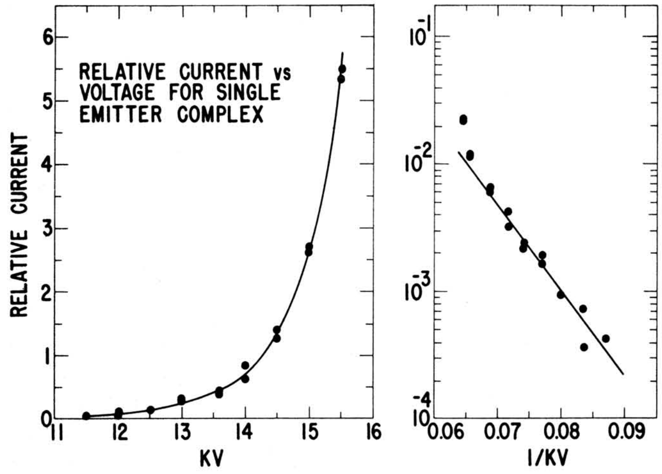

Fig. 8 Linear and Fowler-Nordheim plots of the emission from the particle of Fig. 7. β = 230.

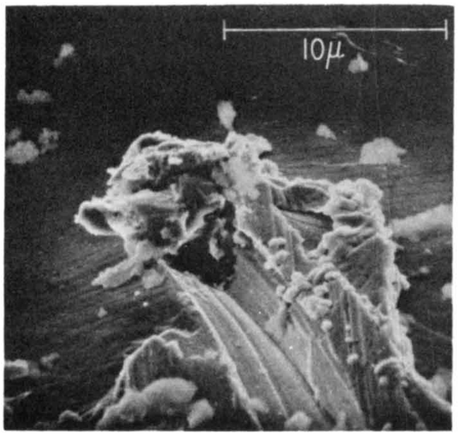

Fig. 9 Part of an emitting cluster on a copper electrode showing an embedded particle at the terminus of a scratch.

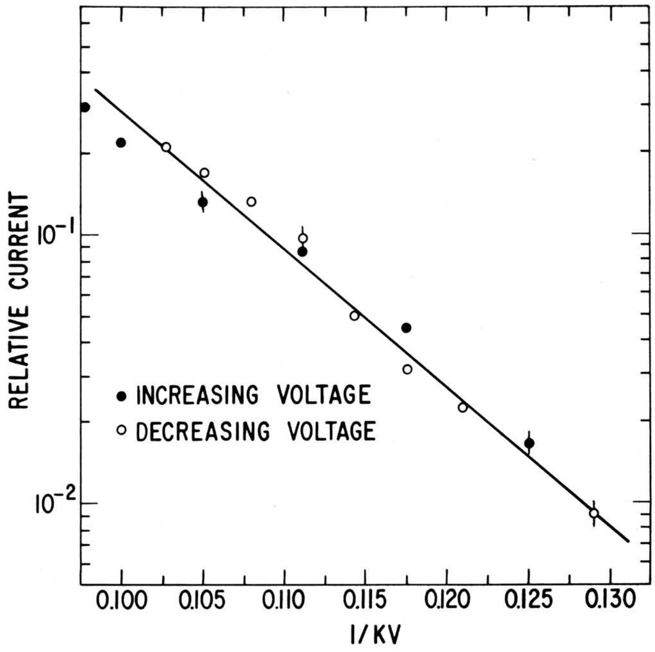

Fig. 10 Fowler-Nordheim plot of emission from the cluster shown in part in Fig. 9.

While it is possible to calibrate the current measuring system in absolute values, this was not done in the present case since our primary interest was in the voltage dependence of the current. It is useful, however, to know what order of magnitudes are actually involved. For a gap operating opposite the vapor reacted phosphor screen at 10 kV, a single emitter will produce just visible light to the eye at about 10^{-10} amp. This light from the phosphor becomes bright and easily seen in the mid 10^{-10} amp range. Both Fowler-Nordheim plots discussed here were obtained with emission currents below 10^{-9} amp.

COMMENTS AND CONCLUSION

The role of insulating particles in the precipitation of breakdown in low-pressure devices has been suggested many times. This idea can at least be traced back as far as Kingdon and Lawton(16) who, acting upon a suggestion by Langmuir,(17) included insulators in their description of backfires in mercury arc rectifiers. The results of the present report would appear to support the view that insulating particles can adversely affect the performance of electrodes in vacuum. The results further show that emission from such embedded particles can at least approximately follow the Fowler-Nordheim equation and yield enhancement factors that might be considered reasonable for metallic emitters. The fit of the emission may be more than accidental in that current could well be produced by the enhanced field at the junction of an insulator and the parent metal surface in which it lies. One might even postulate the further enhancement of the field at the junction by initial low-level emission striking the insulator surface and producing secondary emission between the first and second crossover points on the secondary emission characteristic for the insulator. This mechanism has already been described for insulating posts compressed between two electrodes in vacuum.(18) Such speculation, however, should not be considered as the primary purpose of this work.

Our intent has been to describe techniques for the detailed study of microscopic emitting areas on the cathode. Our choice of lead as an anode transfer metal suits our present purposes, but other metals may be more appropriate. Our results thus far have suggested emitters containing what we believe to be insulating components. We believe, however, that the procedures outlined here or some variation of them would be useful in detecting metallic emission areas as well.

ACKNOWLEDGMENTS

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