

[54] **METHOD AND APPARATUS FOR LIMITING FIELD-EMISSION CURRENT**

[72] Inventor: Wayne L. Lees, Lexington, Mass.

[73] Assignee: The United States of America as represented by the Administrator of the National Aeronautics and Space Administration

[22] Filed: Dec. 11, 1970

[21] Appl. No.: 97,343

Related U.S. Application Data

[63] Continuation of Ser. No. 763,744, Sept. 30, 1968, abandoned.

[52] U.S. Cl. 313/336, 313/351, 313/309, 315/36

[51] Int. Cl. H01j 1/16, H01j 19/10

[58] Field of Search. 313/306, 307, 308, 309, 325, 313/336, 351; 315/35, 36; 328/8

References Cited

UNITED STATES PATENTS

2,692,948 10/1954 Lion.....313/309 X

3,484,643 12/1969 Link et al.....313/309
3,530,271 9/1970 Ullmann et al.....313/353 X

FOREIGN PATENTS OR APPLICATIONS

1,028,351 5/1966 Great Britain.....313/309

OTHER PUBLICATIONS

A Thin-Film Field Emission Cathode, by C. A. Spindt; Journal of Applied Physics, Vol. 39 No. 7 pp. 3504- 3505 June 1968.

Primary Examiner—John W. Huckert

Assistant Examiner—Andrew J. James

Attorney—Monte F. Mott, Wilfred Grifka, John R. Manning and Paul F. McCaul

[57] **ABSTRACT**

Self-protected electrodes which inherently limit field-emitted currents to a safe value and also stabilize such currents are disclosed. The electrodes are characterized by a plurality of columnar conductors connected at one end to a common potential source. The electrodes are insulated from one another along their lengths whereby the effective or exposed surfaces thereof are subdivided into a mosaic of conducting patches which are insulated from one another.

10 Claims, 8 Drawing Figures

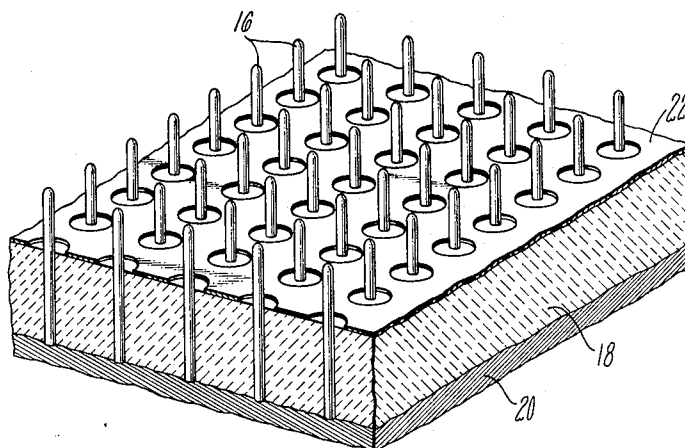


FIG. 1A

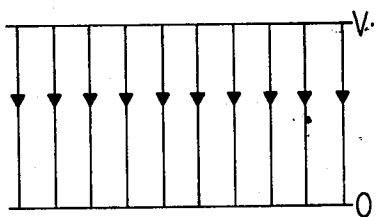


FIG. 1B PRIOR ART

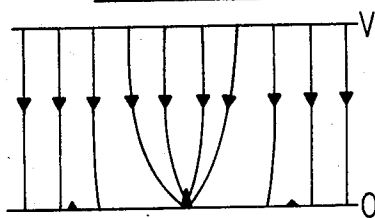


FIG. 1C

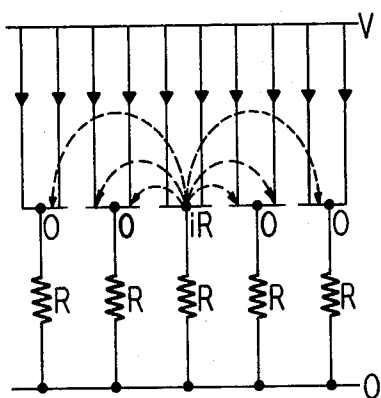


FIG. 1D

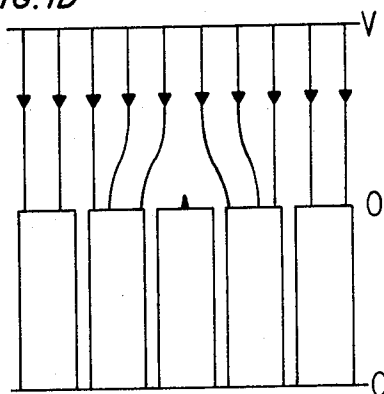
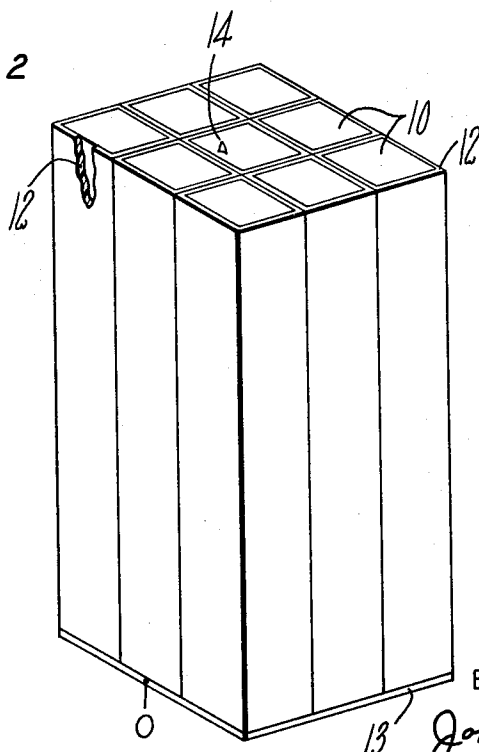


FIG. 2



INVENTOR
WAYNE L. LEES

BY *John R. Manning*
ATTORNEYS

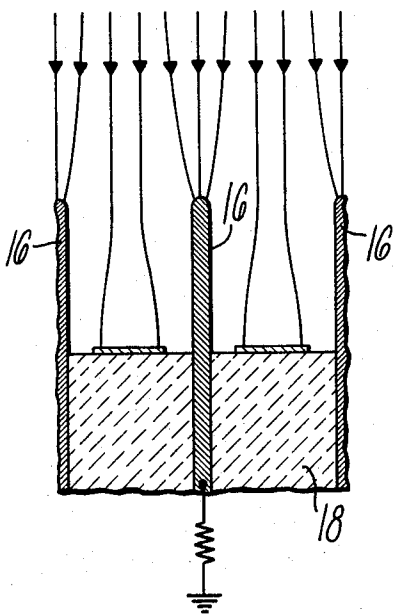
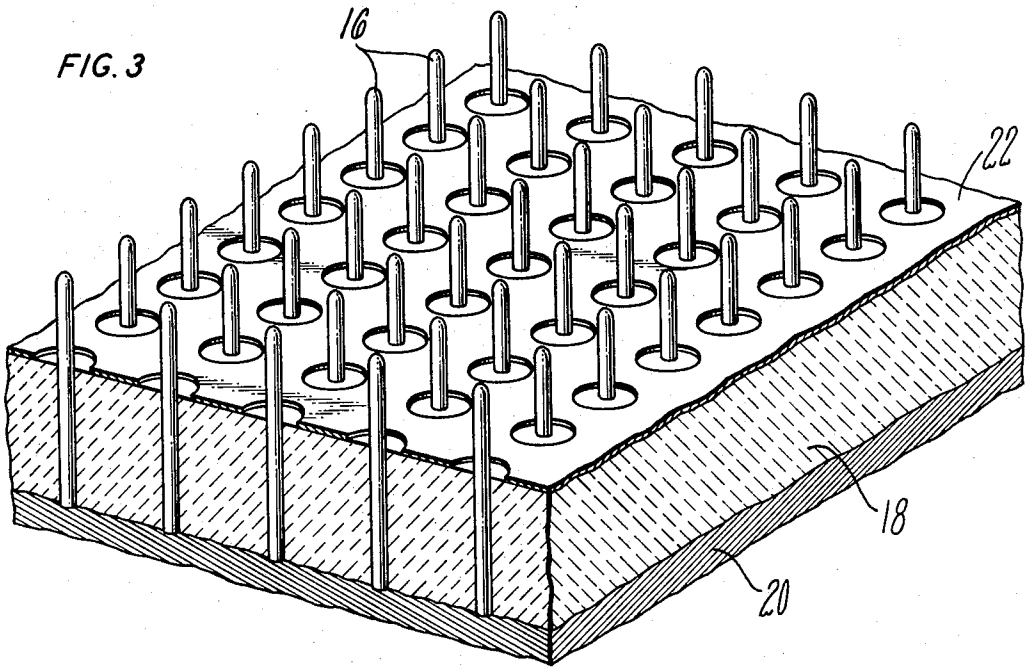


FIG. 4A

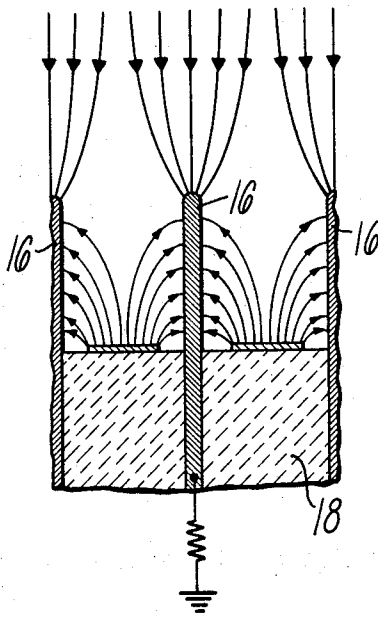


FIG. 4B

John R. Manning
John R Manning

METHOD AND APPARATUS FOR LIMITING FIELD-EMISSION CURRENT

This is a continuation of Ser. No. 763,744, filed Sept. 30, 1968, now abandoned.

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed to self-protecting electrodes. More particularly, the present invention relates to the limiting to a safe value and/or the stabilization of field-emission currents such as those which may be associated with inherently present but undesired protrusions on the surfaces of electrodes of high vacuum devices. Accordingly, the general objects of the present invention are to provide novel and improved methods and apparatus of such character.

2. Description of the Prior Art

While not limited thereto in its utility, a principal object of the present invention is to limit the current of the concentrated arc formed at the cathode of evacuated electronic devices when vacuum electric breakdown occurs. In the prior art, it has been common practice to limit the average current in the pulse occurring upon breakdown by including in the cathode circuit a series connected resistance or inductance having an impedance so large that the concomitant electrode-potential pulse is comparable with the potential before breakdown. This practice, however, allows at least the energy stored in the electrode charge to be dissipated in the arc with consequent electrode damage.

The present invention can be described best with reference to the mechanism of vacuum electric breakdown. Vacuum electric breakdown is the uncontrolled passage of a surge of electric current between two conductors separated by an evacuated gap. When a potential difference is established between two such conductors, the electric fields at the conductors' surfaces are calculable. Such fields, calculated in terms of gross surface features, the so-called macroscopic electric fields, attain magnitudes typically on the order of 0.1 to 1 megavolt per centimeter at the cathode before breakdown occurs. The actual vacuum breakdown or arcing between electrodes, since it occurs when the gas density in the vacuum is too low to support a glow discharge, must be attributed to the pulling of electrons from the cathode by the electric field. This phenomenon is known as field emission. The fields required at a cathode in order for appreciable field-emission current to flow, however, are several hundred times as strong as the fields that may be predicted on macroscopic surfaces. Recent studies have supported the assumption that, in order for these high field strengths to be present, vacuum sparking must accordingly be initiated at very small projections, not otherwise visible, occurring on gross electrode surfaces whose macroscopic fields were of comparatively low strength.

Thus, it is now well accepted that sparks in a high vacuum arise from sharp, field-enhancing projections on the conductive cathode surfaces involved. Typically, vacuum electric breakdown is preceded, as the field strength between a pair of electrodes is increased, by field-emission current. This phenomenon may be more clearly understood by reference to FIGS. 1A and 1B of the accompanying drawing. FIG. 1A is a representation of an ideal uniform field between a pair of electrodes separated by an evacuated gap. FIG. 1B represents field variations which, in actual practice, occur. The lower electrode or cathode of FIG. 1B has protrusions on its surface. It is to be noted that no electrode surface is free of these field-enhancing projections. For example, tests have been made on single-crystal tungsten which has been electropolished to remove mechanically strained metal and trapped abrasive:

When employed as a cathode, such a tungsten electrode was found to possess field-emitting projections which were not apparent until the field was applied. As may be seen from FIG. 1B, the protrusions on the electrode surface will concentrate electric flux at their tips, to some extent shadowing the adjoining electrode surface, so that the field at the microscopic tip is greatly enhanced. As a result of these high local fields, field emission from these protrusions will occur.

As is well known, field emission is the escape of electrons through the surface of a conductor into a sufficiently high attractive field. This field must be at least 10 million volts per centimeter to extract measurable current from most metals. As the field at the electrode is increased, the field-emitted current increases very sharply until, at a tip field on the order of 10^8 Volts per centimeter with a corresponding field-emitted current density on the order of 10^8 Amperes per centimeter squared, the field emission becomes unstable and the current increases quickly by several decades. The resultant vacuum electric breakdown, characterized by a spark or arc, is limited typically by the destruction of the emitting protrusion and of a portion of the electrode surface. If the electrodes are supplied from a source of low impedance, as is necessary in many technical applications, the breakdown can do substantial damage to the electrodes before the current is interrupted by protective devices.

It is also to be noted that the destruction of a portion of the electrode surface which occurs upon vacuum electric breakdown results in the production of vapor. As will be obvious, accumulation of a sufficient concentration of vapor between the electrodes will result in a glow discharge with corresponding destructive breakdown currents. Also, while sparks destroy their own initiating points, they tend to splash metal and thus to establish new surface protrusions. This effect leads to the reduction of the field strength at which a subsequent vacuum electric breakdown will occur.

SUMMARY OF THE INVENTION

The present invention overcomes the above-discussed and other disadvantages of the prior art and in so doing provides a novel, self-protective electrode which may also be used as a stabilized field-emission source. The electrodes of the present invention are characterized by a plurality of columnar conductors which, to a spatially displaced anode, will appear as a mosaic of conducting patches insulated from one another. The exposed surfaces of the conductors which comprise the present electrodes are microscopic but remain large when compared to typical field-enhancing protrusions. Also, each of the conductors is very long when compared to its effective surface area, the opposite ends of each conductor being connected to a common potential source.

When employed as a stabilized field-emission electrode, the electrodes of the present invention may also be characterized by a control film or electrode which surrounds but is insulated from the base of each of the individual conductors. The control film may serve to provide an equipotential against which tip-potential fluctuations are stabilized and may also be employed to control the level of field emission from each conductor to a common value.

It is therefore an object of the present invention to limit the current of the concentrated arc formed at a cathode in vacuum electric breakdown.

It is also an object of the present invention to destroy field-emitting protrusions on an electrode surface in such a manner that insufficient vapor to maintain an arc is produced.

It is another object of the present invention to provide electrodes which are comprised of a plurality of conducting columns, the individual columns having sufficient resistance to provide a limiting potential shift with the maximum allowable field-emission current.

It is a further object of the present invention to stabilize field-emitted currents.

BRIEF DESCRIPTION OF THE DRAWING

The present invention may be better understood and its numerous advantages will become apparent to those skilled in the art by reference to the accompanying drawing wherein like reference numerals refer to like elements in the various figures and in which:

FIG. 1, comprising the FIGS. 1A, 1B, 1C and 1D, is a schematic presentation of the problem solved by the present invention and its manner of solution;

FIG. 1A representing the theoretical field distribution between a pair of electrodes in a vacuum;

FIG. 1B representing the actual field distribution in the prior art, and

FIGS. 1C and 1D representing the modifications in field strength resulting from use of the present invention;

FIG. 2 is an isometric view of a first embodiment of the present invention;

FIG. 3 is an isometric view, partly in section, of a second embodiment of the present invention employed as a stabilized field-emission electrode; and

FIGS. 4A and 4B are partial, cross-sectional views of the embodiment of FIG. 3 depicting field distribution for the embodiment of FIG. 3 under each of two operating conditions.

DESCRIPTION OF THE PREFERRED EMBODIMENT

As discussed above, FIG. 1A depicts the ideal field distribution between a pair of electrodes separated by an evacuated gap whereas FIG. 1B depicts the actual field distribution, prior to vacuum electric breakdown, which arises due to field-enhancing projections on the electrode surface. As also previously noted, it is an object of the present invention to prevent vacuum electric breakdown and, in so doing, to destroy or erode the field-enhancing projections on the electrode surface slowly and smoothly, thereby obviating the danger of establishing new points (through explosive destruction of a projection) and insuring against the production of sufficient vapor to maintain a glow discharge. Thus, the electrode construction of the present invention is characterized by the self-limitation of field-emitted current.

The manner in which the foregoing is accomplished may be understood from a consideration of FIGS. 1C and 1D. As alluded to above, field-emission current is very sensitive to the magnitude of the field acting at the electrode surface. Because of this, minor fractional changes in field strength can alter the field-emitted current by several decades. Also, it must be remembered that the field-enhancing projections which characterize all electrode surfaces are of microscopic size. Accordingly, since each protrusion is very small, the distance over which the macroscopic field must be varied in order to control field-emission from each protrusion is correspondingly small. As is well known, high fields can be developed over short distances with small potential differences. Thus, in accordance with the present invention and as may be seen from FIG. 2, the effective surface of an electrode is subdivided into a mosaic of conducting patches which are insulated from one another and which have dimensions that are microscopic but remain large compared with the size of the field-enhancing protrusions. Each of these conducting patches is connected to a base or common-potential plane through separate resistive columns, such columns being indicated in FIG. 1C by the resistors R. A field-enhancing projection on a conducting patch which emits current i will make that patch more positive than its neighbors by iR , where R is the column resistance. This potential difference will reduce the applied field at the emitter by Ri (b/a), where a is the inscribed radius of the patch, and b is a geometric factor.

To restate the foregoing, when a potential is applied, the field at first is distributed uniformly over the conducting surface-patches formed by the ends of the conducting columns, as indicated at FIG. 1A, except for local enhancement at a protrusion, as shown in FIG. 1B. When the field has been in-

creased until a sharp protrusion on one patch begins to emit electron current i , supplied through its column resistance R , that surface patch becomes more positive than its neighbors by iR , thereby creating an opposing field at its surface as shown by the broken lines in FIG. 1C. The resultant gross field is reduced at the emitting patch, as shown in FIG. 1D, thereby limiting the field-emitted current. It is to be noted that the field-emitted current will not be eliminated but rather will be self-limited to a safe value whereby field emission from the surface protrusion will continue smoothly until the current-heated protrusion has been eroded away or rounded, the phenomenon of thermal evaporation being known in the art.

With reference now to FIG. 2, a first embodiment of the present invention is shown. The embodiment of FIG. 2 comprises a plurality of square shaped conductors 10 which are insulated from one another by means of insulation 12. Conductors 10 are electrically connected to one another at first ends by being in contact with conductive metal plate 13. A centrally located one of electrodes 10 is shown as having a field-enhancing projection 14 on its second or upper end, the second ends of the conductors forming the conducting patches of the resulting mosaic electrode. It should be noted that, for proper operation of the invention, it is not necessary that the projection 14 be centered in the mosaic patch as indicated in FIG. 2. Rather, the reverse field developed by the increment iR and therefore the current-limiting effect increases as the projection is placed nearer the edge of the conducting path. It may be shown that the reverse field at the center of a conducting patch is on the order of Ri divided by a , a being the inscribed radius of the patch. For flat-top columns with negligible insulator thickness, the field-emission current i reduces the applied field by:

$$i \left(\frac{\rho h}{a^3} \right) \left(\frac{b}{c} \right) \quad (1)$$

where:

b/c is the column shape factor,

h is column height,

ρ is column resistivity,

ca^2 is column cross-sectional area. 10^{-6}

If a is 1 micron, then Ri should become on the order of 10 volts when i approaches the intended field-emission current limit. If the conducting column under the patch having the field-enhancing protrusion has a cross-sectional area of 10^{-116} cm² and a length of 1 centimeter, and is formed of a material having a resistivity of 10 microhm-centimeters, then its resistance R becomes 1,000 ohms and a 10 volt excursion Ri requires a field-emission current of 10 milliamperes. Such a current would approach typical breakdown density if emitted from an area of 10^{-10} cm². The uncontrolled current rise at breakdown, however, would be prohibited by the attendant increase in the potential difference Ri and the resultant greatly increased opposing field. Accordingly, the effect of a high but limited field-emission current would not be a spark or other catastrophic breakdown but rather would be a simple ablation and rounding of the emitting protrusion so that its field-enhancement factor would be reduced. It should be noted that the resistivity of the insulation material 12 must be high enough so that the leakage current to adjoining columns is small compared with i .

While the individual conducting columns 10 have high resistances, the macroscopic conductivity of the columnar electrode in a direction perpendicular to its surface is approximately that of the solid conductor material. The ratio of this conductivity to that of the solid is the ratio of the conductor cross-section area to the combined conductor and insulator cross section. Thus, for example in a vacuum capacitor, such a columnar electrode can carry a large radio frequency current density, on the order of 100 amperes per centimeter squared, without undue heating while any breakdown pulses superimposed on this current are unidirectional and will be limited to a few milliamperes.

As will be obvious from the foregoing discussion, the conducting columns of the embodiment of FIG. 2 must be of small size since the reverse field produced by a potential increment R_i varies inversely with the radius of the patch while the resistance R in turn varies inversely with the square of this radius. The embodiment of FIG. 2 may be produced, for example, by commercial techniques for drawing metallic wires in a glass matrix. These techniques are known and are similar to those employed, for example, in forming fiber-optic bundles. Another technique which may be employed in the production of the embodiment of FIG. 2 and which preferably would be employed in manufacturing the embodiment of FIG. 3 would be the unidirectional solidification of a eutectic melt. It is known that metallic "whiskers," in either a conductive or nonconductive supporting matrix, may be obtained by freezing certain alloys from a melt in one direction. For further information on the production of such single crystal "whisker" composites, reference may be had to an article entitled "Metals with Grown-in Whiskers" by M. Salkind and F. Lemkey which appeared at pages 52-64 of "International Science and Technology," March 1967 or to an article entitled "Whisker Composites by Unidirectional Solidification" by M. Salkind et al. which appeared at pages 52-60 of "Chemical Engineering Progress," Volume 62, No. 3, March 1966.

Considering now FIG. 3, an electrode array which has been formed by one of the above-noted techniques is shown. As depicted in FIG. 3, the array is to be employed as a stabilized, field emission source. The array comprises a plurality of rod-like conductors 16 supported in an insulating matrix 18. It is, of course, to be understood that the supporting matrix 18 has been chemically etched away to expose the rod-like conductors 16. It is also to be understood that the composite has been suitably sliced so that the lower ends of all of the conducting rods 16 are exposed thereby enabling electrical contact to be made between each of rods 16 and a planar electrode 20. The embodiment of FIG. 3 is also shown as comprising a reference or control film 22 of conducting material which is isolated from each of conductors 16. It is, however, to be observed that control film 22 would not be employed where the electrode is utilized merely because of its superior breakdown limiting characteristics as, for example, in a vacuum capacitor. For such uses, in order to maximize the ratio of effective conductor area to total electrode surface area, it would be desirable to increase the effective surface area of conductive rods 16 by building these elements up through electroplating, or by melting exposed portions of the elements to globular form, with care in either case to insure that the rods would remain electrically isolated from one another at the exposed upper surface of the supporting matrix 18.

It can be shown that a small fractional change of surface field produces a greater fractional change in field-emitted current at low fields than at high. Accordingly, a reverse-field increment that reduces current significantly at an applied field high enough to initiate breakdown is still more effective at lower fields, and therefore the same structure than can limit vacuum breakdown at high field-emission current densities may become, after some modification, a stabilized electron source for field emission at lower current densities. With regard to modification, the major difference is the addition of the control film 22 as shown in FIG. 3. In addition, the step of increasing the effective surface area of the conductors 16 would not, of course, be performed if the device were to be used as a stabilized field-emitting array rather than merely as a self-limiting electrode. The protruding tips of the conductors 16 will, of course, concentrate the field in the same way as do the random protuberances, such as projection 14 of FIG. 2, on which breakdown occurs. In the preferred embodiment the conducting rods 16 are made small enough so as to produce the required field enhancement even when rounded at their ends. This rounded form, in which the current density in the "resistor" columns is nearly as large as that in the field-emitting tips, will develop the greatest stabilizing voltage in response to a current increment.

The control film 22 serves both to provide an equipotential against which tip-potential fluctuations are stabilized and also to control the common level of field emission. Since the broad surface offered by control film 22 provides a near termination for electric flux lines originating on the tip of a conductor 16, a potential rise due to increased current flow in the conductor leads to a reverse field larger and more predictable than would be developed if the neighboring surfaces were only the other conductors and an exposed insulating surface. In particular, an exposed insulating surface is undesirable since it would be the source of poorly controlled fields from the slowly migrating charges with resulting drift of the field-emission currents. The control film 22 also serves to adjust the field applied to all conductor tips simultaneously through the vehicle of regulating tip potential with respect to conducting base 20. It must be observed, of course, that if the conductors 16 protrude so far that most of the lines of flux terminate on adjoining conductors, the control film will have little influence.

The effect on the fields at the rounded ends of conductors 16, as the control film is made more positive than the conductor tips, is shown schematically in FIGS. 4A and 4B. In FIG. 4A, the R_i voltage at the tips of conductors 16 is zero. As the control film potential is increased in a positive direction, the concentration of flux lines at the tips of conductors 16 is increased by the addition of the lines from the film that terminate on the protruding conductors 16. Presuming that the total flux from the remotely located anode is not changed appreciably, the resulting increased tip field is accompanied by a decrease of anode flux to the control film 22 as shown in FIG. 4B. Obviously, if the control film is made more negative, the anode flux to the control film increases while the tip field decreases. Thus, it may be seen that the combined action of the control film and the self-limiting effect of the columnar conductors results in a controllable field-emission electrode which is stabilized and which will not be subject to catastrophic breakdown.

While preferred embodiments have been shown and described, various modifications and substitutions may be made thereto without departing from the spirit and scope of the present invention. Accordingly, it is to be understood that the present invention has been described by way of illustration and not limitation.

What is claimed is:

1. A self-protecting electrode for use in rarified gaseous environments comprising:
 - a plurality of spaced elongated columnar conductors, each of the columnar conductors having first and second ends and having sufficient resistance between the ends to provide a predetermined potential shift in the potential of one end with respect to the other in response to the flow of a predetermined field-emission current through the respective columnar conductors, the distance between any pair of said conductors in a direction perpendicular to their lengths being greater than the length of either conductor in said direction;
 - insulating material for insulating said conductors one from another along their lengths with at least a portion of each conductor extending from its first end being surrounded by said insulating means and inhibited from exposure to the other conductors; and
 - means for electrically connecting the first ends of said conductors to a common point.
2. The electrode of claim 1 wherein said conductors are of substantially equal length, are very long when compared to their cross-sectional area and the second ends of said conductors being of substantially the same cross-sectional shape and area.
3. The apparatus of claim 2 wherein said insulating material extends the length of said conductors, with only the second ends of said conductors being exposed and each conductor along its entire length being covered by said insulating means to inhibit its exposure along its length to adjacent conductors.
4. A self-protecting electrode for use in rarified gaseous environments comprising:

a plurality of columnar conductors, each of the columnar conductors having first and second ends and having sufficient resistance between the ends to provide a predetermined potential shift in the potential of one end with respect to the other in response to the flow of a predetermined field-emission current through the respective columnar conductors;

insulating material for insulating said conductors, one from another along said lengths, said insulating material extending along a portion of said conductors from their first ends, the second ends of the conductors and portions thereof adjacent said second ends extending above the insulating material; and

means for electrically connecting the first ends of said conductors to a common point.

5. The apparatus of claim 4 further comprising:

a layer of conductive material disposed on the surface of the insulating material through which the conductors extend, said layer of conductive material being electrically isolated from said conductors.

6. An electrode comprising:

a substantially flat electrically conductive base member;

a plurality of electrically conductive columnar members, each extending vertically from said base member with a first end in electrical contact with said base member and an opposite second end remote from said base member; and

insulating material extending from said base member and surrounding at least a portion of each columnar member

from its first end toward its second end, whereby at least a portion of each columnar member is inhibited from exposure to the other columnar members, the distance between any pair of said columnar members in a direction parallel to said base member being greater than the width of either columnar member in said direction.

7. The electrode of claim 6 wherein said columnar members are of substantially equal length, are very long when compared to their cross-sectional area and the second ends of said columnar members being of substantially the same cross-sectional shape and area.

8. The apparatus of claim 7 wherein said insulating material extends the entire length of said columnar members, with only the second ends of said columnar members being exposed and each columnar member along its entire length being covered by said insulating material to inhibit its exposure along its length to adjacent members.

9. The apparatus of claim 7 wherein said insulating material extends along a portion of said columnar members from their first ends, the second ends of the columnar members and portions thereof adjacent said second ends extending above the insulating material.

10. The apparatus of claim 9 further comprising:

a layer of conductive material disposed on the surface of the insulating material through which the columnar members extend, said layer of conductive material being electrically isolated from said columnar members.

* * * * *

35

40

45

50

55

60

65

70

75