Emission uniformity enhancement between microfabricated tips in cold cathode arrays

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The current–voltage characteristics can vary significantly between individual microfabricated tips in as-fabricated arrays of cold cathodes. Such emission nonuniformity is undesirable in device applications. We have shown that *in situ* tip self-heating by the emitted electron current can be used to make the current–voltage characteristics of microfabricated field emitter tips nearly identical to one another. The improved emission uniformity will allow for more reliable array operation at increased electron emission current densities. © *2001 American Vacuum Society.*
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It has long been known that the current–voltage ($I-V$) characteristics vary between tips in a microfabricated array of cold field emission cathodes. This nonuniformity was first inferred from the observation that the average current per tip that could be reliably extracted from an array of tips decreased with the number of tips in the array.[1] This decrease in reliable average current per tip indicates that some fraction of the tips approach current densities at which emission instabilities develop, while others operate at current densities well below this level. More recently, imaging of the emission distribution from single tips in an array has directly shown the levels of emission nonuniformity.[2] In some cases, where pure proximity focusing is not used, direct imaging can overestimate emission nonuniformity because only nearly paraxial beams from the tip are imaged. Thus, highly off-axis emission may be present but not pass through the imaging system. That is a tip may appear to not be emitting when it actually is. Nevertheless, estimates of the number of tips ''participating'' in the emission process in an array can be as low as a few percent dependent, of course, on the total emission current.[2] Clearly, the increase in the number of tips participating in the emission process as the voltage is increased indicates the degree of variation in the $I-V$ characteristics between tips.

Besides the possible ramifications of the resulting spatial nonuniformity, a large variation in the $I-V$ characteristics between tips in an array decreases the average current per tip that can be extracted without inducing voltage breakdown events. Thus, for a given tip packing density, the total current density that can be extracted from an array is not proportional to the array size, which is clearly undesirable.

Early in the development of field emission cathode-based devices, arrays of etched-wire tungsten tips were investigated by Dyke and co-workers as possible cathodes for flash x-ray sources and microwave devices.[3,4] The need for large total emission currents required the use of arrays of these tips. Dyke realized that the slight differences between tips that arose even when the arrays of tips were electrochemically etched simultaneously could be largely eliminated by annealing the tips at high temperatures.[3] Besides the removal of surface contaminants, the resulting tip blunting and smoothing by surface self-diffusion was found to be self-limiting. That is, given initially similar tip–shank profiles, all tips asymptotically approached a final equilibrium end form having similar radii. This technique was successfully employed to enhance emission uniformity between the etched-wire tip arrays.[3]

We recently investigated using the extracted electron emission current to heat microfabricated emitter tips *in situ* and showed that this process leads to appreciable tip surface cleaning by contaminant thermal desorption and recrystallization by surface self-diffusion at temperatures estimated to be on the order of 800 °C.[5] Even though surface diffusion occurs in the presence of a high electric field, tip blunting is observed. To zeroth order, tip blunting and smoothing are expected because the average microfabricated molybdenum tip radius is on the order of 200 Å, and the geometrical nonuniformities leading to emission nonuniformity typically have smaller characteristic dimensions. Thus the surface energies associated with the geometrical nonuniformities exceed their field energy, and they should anneal back into the tip surface by thermally activated surface self-diffusion.[6,7] In light of our results for microfabricated tip self-heating and those of Dyke *et al.*, it is reasonable to expect that tip annealing via self-heating could significantly enhance the emission uniformity between microfabricated tips having quite different as-fabricated $I-V$ characteristics.

The experimental chamber was one of two glass and metal field emission microscopes, which operated at a base pressure below 10^{-10} Torr following a 12 h system bakeout at 200 °C. The cathodes were Spindt-type molybdenum single-tip emitters mounted on T0-5 headers. Emitter tip pulsing and electron emission imaging were conducted as described previously.[5(b)] Square-wave 100 μs negative-voltage pulses were applied to the tips relative to the grounded gate electrode at a frequency of 5 Hz. The time for

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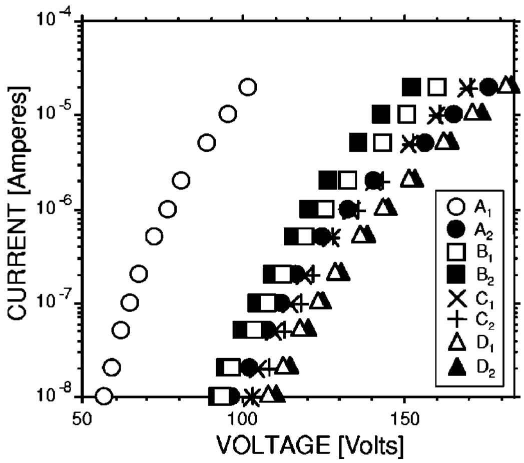

FIG. 1. $I-V$ characteristics for two microfabricated single-tip cathodes subjected to simultaneous pulsed current processing: cathode 1: 39+183F-1B3; cathode 2: 39J+163F-3S. Curve A_x, cathode x as fabricated; curve B_x, cathode x following current pulsing; curve C_x, cathode x following further current pulsing; curve D_x, cathode x following additional current pulsing.

which the cathodes were operated in the pulsed mode, t_{on}, is the duty cycle multiplied by the total elapsed time. The base (tip) and gate electrodes of the single-tip cathodes were connected in parallel with one another so that they were pulsed simultaneously.

Figures 1 and 2 show the $I-V$ data and Fowler–Nordheim (FN) plots of two single-tip cathodes during changes that occurred during emitter tip self-heating. Curve A_1 and Curve A_2 are the $I-V$ characteristics of the as-fabricated single-tip cathodes, number 1 and number 2, respectively, following their installation in the vacuum chamber, chamber bakeout, and operation at 20 μA (60 Hz) of emission current for ~40 h to condition the cathode and

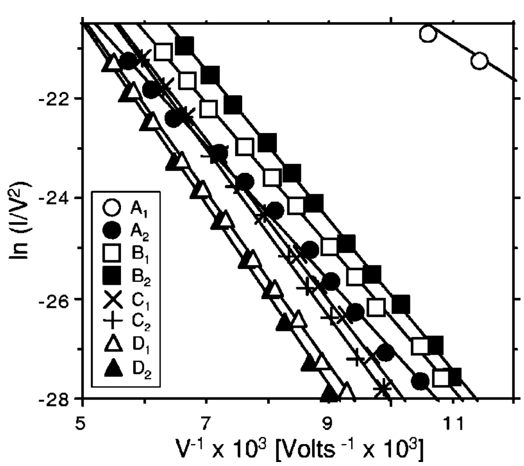

FIG. 2. $I-V$ data of Fig. 1 plotted in FN coordinates. Curve A_x, cathode x as fabricated (A_1: $a=6.14\times10^{-6}$ A/V^2, $b=-800$ V; A_2: $a=1.37\times10^{-6}$ A/V^2, $b=-1350$ V); curve B_x, cathode x following current pulsing (B_1: $a=6.14\times10^{-6}$ A/V^2, $b=-1440$ V; B_2: $a=1.85\times10^{-5}$ A/V^2, $b=-1500$ V); curve C_x, cathode x following further pulsing (C_1: $a=1.12\times10^{-5}$ A/V^2, $b=-1630$ V; C_2: $a=1.51\times10^{-5}$, $b=-1700$ V); curve D_x, cathode x following further pulsing (D_1: $a=8.29\times10^{-6}$ A/V^2, $b=-1740$ V; D_2: $a=1.12\times10^{-5}$ A/V^2, $b=-1810$ V).

provide stable $I-V$ characteristics. Only a portion of the FN data for curve A_1 is plotted in Fig. 2 to show the other data in more detail. The significantly different FN a and b parameters, from the FN equation $I=aV^2e^{(-b/V)}$, where I is the emitter current and V the base-to-gate voltage, are evident. One can see that, at a given voltage, the emitted currents differ by roughly a factor of 10^3.

Following collection of the $I-V$ data, the cathodes were connected in parallel and emission current pulsing was initiated. After pulsing at a combined current I_{total}, of ~500 μA (t_{on}=30 s), the emission current had decreased to ~400 μA (cathode 1 ~330 μA, Cathode 2~70 μA). I_{total} was then increased to ~800–900 μA (t_{on}=10 s). At this level the current was sufficient to anneal cathode 1, yet only clean cathode 2 by thermal desorption.[5(b)] Curves B_1 and B_2 are the $I-V$ characteristics of the cathodes at this point. Note that now the voltage required for a given current is lower for cathode 2 than it is for cathode 1.

With continued pulsing at elevated emission levels (I_{total} =1.5 mA; t_{on}=27 s), both cathodes anneal back (blunt) together, curves C_1 and C_2 in Figs. 1 and 2. The $I-V$ characteristics are now nearly indistinguishable from one another. With further self-heating (I_{total}=2.0 mA; t_{on}=31 s), the cathodes again stabilize with the $I-V$ characteristics of the two cathodes remaining very similar, curves D_1 and D_2 in Figs. 1 and 2.

With the eight sets of cathodes studied to date, the details of the changes in the $I-V$ characteristics during cathode annealing, and the currents required to induce those changes, depend on the initial $I-V$ characteristics. However, the end result of pulsed heating is very similar cathode $I-V$ characteristics as shown above.

We have demonstrated that emitter tip self-heating can be used to make the $I-V$ characteristics of microfabricated cathode tips nearly identical even though the difference was very significant in their as-fabricated form. The applicability of this procedure to enhance emission uniformity from arrays of microfabricated tips is clear. By enhancing the emission uniformity in arrays, the total available current for a given number of tips, the emitted current density for a given tip packing density, and the operational reliability will all be increased.

In another experiment, SRI demonstrated operation of a single-tip cathode at a current level of 100 μA for over 1 yr. Thus, by making the emission from arrays very uniform, a 10^4 tip array having a 4 μm pitch should reliably produce current densities in excess of 500 A/cm^2.

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