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Spindt Cathode Tip Processing to Enhance Emission Stability and High-Current Performance

C. A. Spindt, P. R. Schwoebel, and C. E. Holland

Abstract

The extracted field emission current can be used to controllably heat microfabricated cold field emission cathode tips. The heating can be sufficient to smooth and recrystallize the tip surface by surface self-diffusion, and at least partially clean the surface of contaminants by thermal desorption. Self-heating not only allows for the achievement and maintenance of stable emission characteristics, but can be used to make the current-voltage characteristics of microfabricated field emitter tips nearly identical to one another. The resulting improvement in emission uniformity will allow for more reliable array operation at increased electron emission current densities.

Keywords : LCD controller, contrast controller, interpolation filter

1. Introduction

The surface structure and chemical composition of microfabricated field emitter tips govern the current voltage (*I-V*) characteristics by defining the electron-tunneling barrier. These field emitter tips are typically composed of emitting surfaces having a structure that exhibits few signs of crystallinity and a chemical composition that is essentially unknown. Adsorption of common contaminants on the emitting surface can increase the average work function and the emission current noise. As a result, the following operational problems have been identified in some field emitter array based device development efforts: (1) a roughly monotonic decrease with time of the mean emission current at constant applied voltage and (2) fluctuations of the emission current at a constant voltage about this decreasing mean. The results of these operational problems are poor time correlation between the applied voltage and emitted current and the need to gradually increase the applied voltage to maintain a given current.

It has been known for many years that the current-voltage (I-V) characteristics vary between tips in a microfabricated array of cold field emission cathodes. Besides the possible ramifications of the resulting spatial non-uniformity, a large variation in the current-voltage 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 uniformly proportional to the array size.

Early field emission investigators realized that cathode surface cleaning and annealing stabilized the emission current as a result of smoothing the tip surface and removing surface contaminants. The etched wire tungsten emitter tips used at that time were ideally suited for field emission studies due to their high yield strength and ease of cleaning by simply heating to very high temperatures. When it was necessary to employ arrays of etched wire tungsten tips for high currents in certain device applications, Dyke and coworkers[1] realized that

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emission uniformity between tips in an array could be significantly enhanced by annealing the tips at high temperatures.

We recently investigated[2] 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. In addition we have shown[3] that tip annealing via self-heating could significantly enhance the emission uniformity between microfabricated tips having quite different as-fabricated I-V characteristics. In this paper we review and summarize the results of these studies.

2. Experiment

The experimental chamber was a metal field emission microscope operating 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. During cathode operation, the gate electrode current was always below the 10 nA minimum detectable level for our arrangement. Square-wave 100-μs negative voltage pulses were applied to the tip relative to a grounded gate electrode at a frequency of 5 Hz. The time for which the cathode is operated in the pulsed mode, t_{on}, is the duty cycle multiplied by the total elapsed time. The emission current pulses were capacitively coupled from the phosphor anode (maintained at 2 to 3 kV), passed through a transimpedence amplifier, and viewed on a Tektronix 540D oscilloscope. During current pulsing capacitive coupling between the gate and base electrodes negated the measurement of current, if any, that impinged on the gate electrode.

3. Results and Discussion

3.1 Cathode fabrication with multiple cone depositions

In the course of performing these experiments it became apparent that the emission level at which breakdown and destruction of the emitter tip occurred was often not due to excessive emission, but rather voltage breakdown between the base and gate electrodes. For the high emission-current tests we had been using significantly smaller than normal structures (~ 0.75-μm gate diameter and oxide thickness) in order to minimize the required voltage. Using emitters with the dimensions given above, we found that it was rarely possible to obtain more that ~ 100 μA of emission from a single tip, and initially this was thought to be a maximum possible emission current. However, we also made the important observation that failure usually occurred at about 200 V between the base and gate electrodes regardless of the emission level. Clearly, the voltage that can be applied between the gate and base electrodes in a Spindt cathode is fundamentally limited by the thickness of the dielectric insulating layer between these electrodes. With this in mind, the oxide thickness was increased from ~ 0.75 μm to ~ 1.5 μm, while keeping the gate diameter at 0.75 μm.

The thicker oxide was successful in that the gate-to-base breakdown voltage was increased to the 400 - 450 V range, and emission levels in the 100's of microamps range and higher became a common occurrence. However, this ticker oxide also required an adjustment of the standard emitter-cone fabrication process in order to maintain the 0.75-μm gate diameter that is one of the factors responsible for this high-current performance.

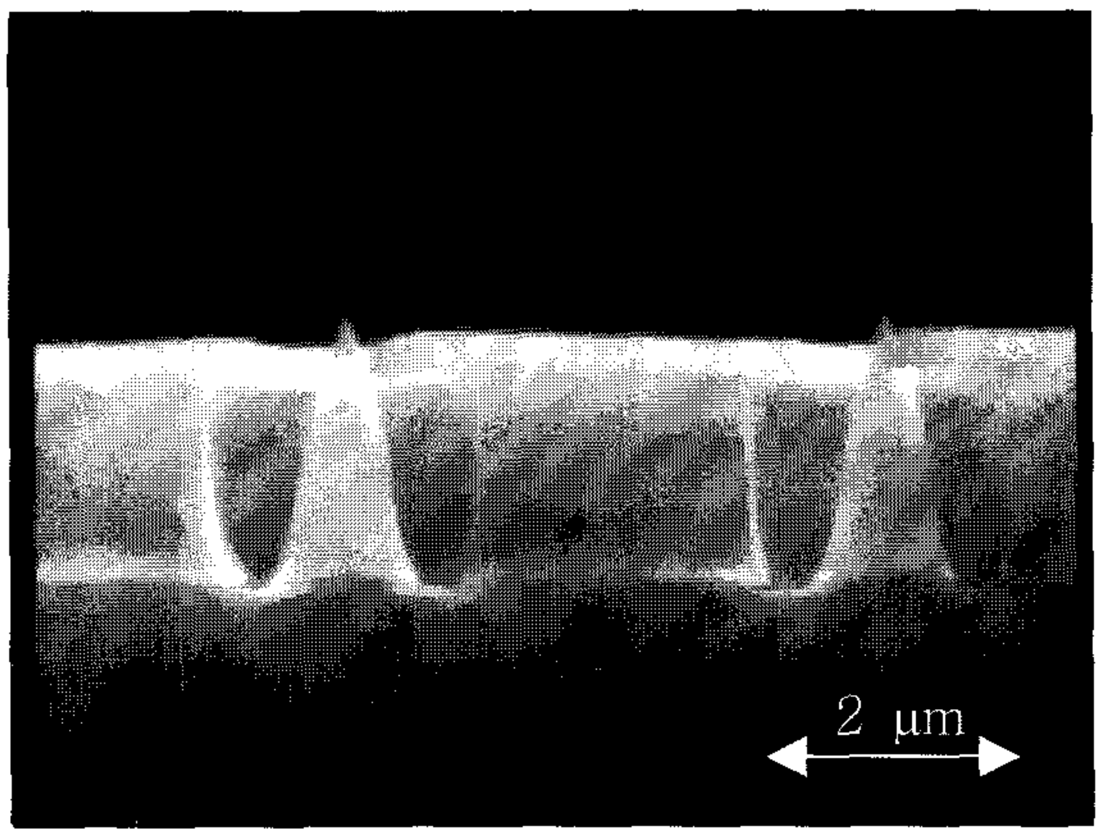

Fig. 1. A scanning electron micrograph of a sectioned Spindt cathode showing a gate to base oxide thickness of ~ 1.75 μm, and gate aperture diameters of ~ 0.8 μm.

The standard Spindt cone-growth process[4] tends to produce emitter cones with an aspect ratio of 1:1. Forming low-voltage tips requires gate holes < 1 μm in diameter. Therefore, it was necessary to modify the cathode growth to produce higher aspect ratio cones. This was done by using multiple cone depositions (i.e., performing the Spindt cone formation process on a cathode structure two or more times), thereby growing cones on top of cones and doubling the cone aspect ratio. Figure 1 is an SEM of cones formed in this way having an aspect ratio of 2:1.

3. 2 Cathode self-heating studies

Fig. 2 and 3 show the I-V data and Fowler-Nordheim (FN) plots of two single-tip cathodes before and after emitter tip self-heating. Curve I_1 and Curve I_2 are the I-V characteristics of the initial, 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, the cathodes provide stable I-V characteristics. Only a portion of the FN data for Curve I_1 is plotted in Fig. 3 to show the other data in more detail. The significantly different FN *a* and *b* coefficients, from the FN equation:

$$I = aV^{2}e^{(-b/V)}$$

Where I is the emitter current and V the base-to-gate voltage, are evident. One can see that, at a given voltage, the initial emitted currents differ by roughly a factor of 10^3.

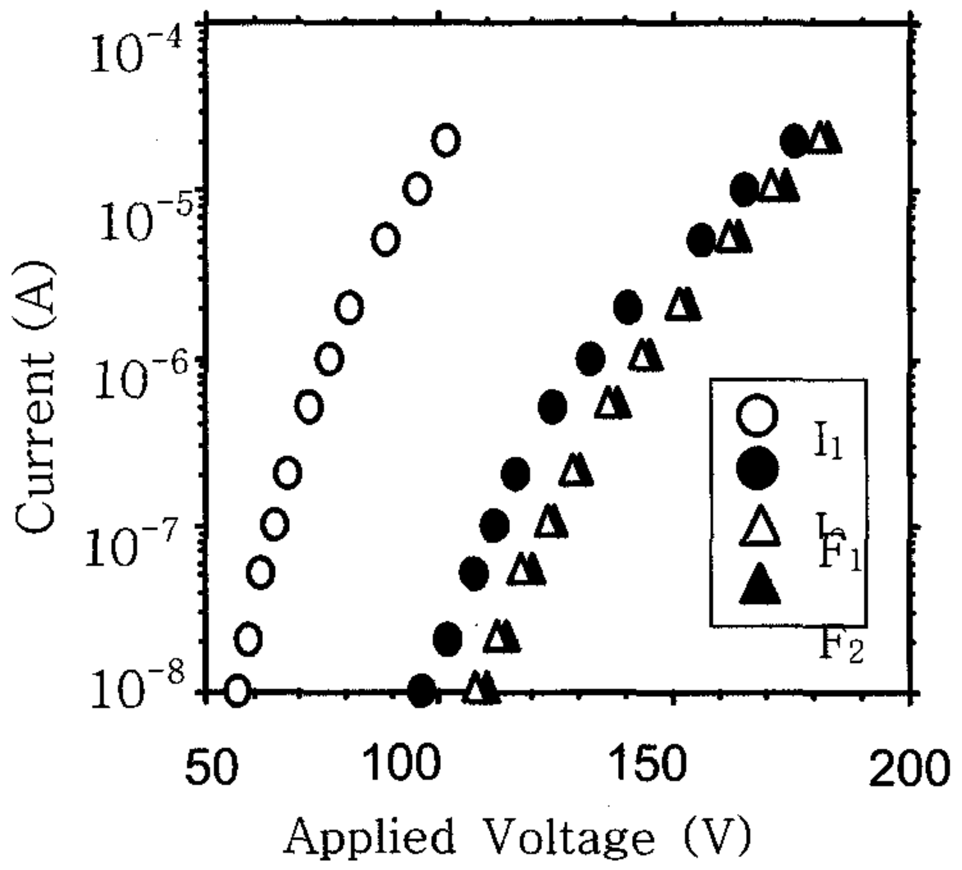

Fig. 2. I-V characteristics for two microfabricated single-tip cathodes characterized individually as fabricated (I_1 and I_2) and after being connected in parallel and subjected to simultaneous pulsed high- current processing (F_1 and F_2).

Following collection of I-V data, the cathodes were connected in parallel and emission current pulsing was initiated. As the combined current at which pulsing was conducted was increased, the I-V characteristics of the two cathodes changed. As pulsed emission current levels of 2 mA were approached, the I-V characteristics of the two cathodes gradually converged and stabilized with the final data nearly indistinguishable from one another, Curves F_1 and F_2 in Fig. 2 and 3.

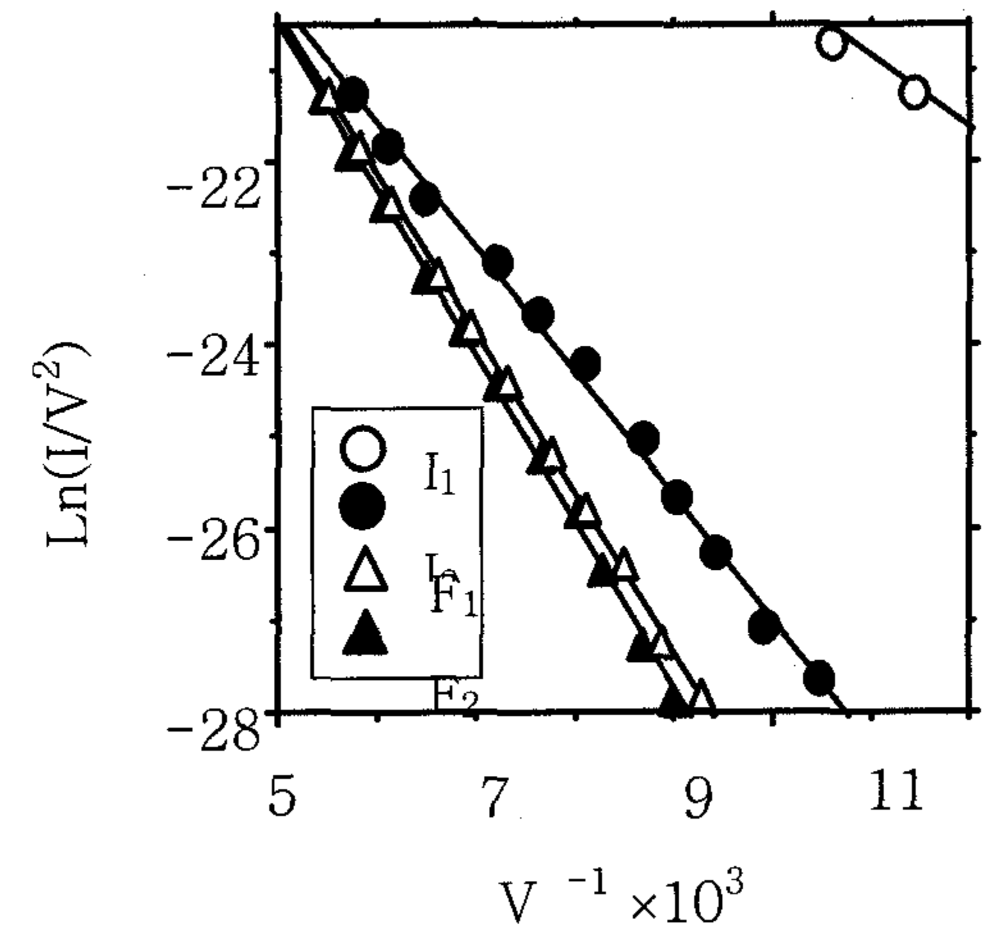

Fig. 3. I-V data of Figure 2 above plotted in FN coordinates. (I_1 and I_2) performance as fabricated. (F_1 and F_2) after high-current processing. FN coefficients: I_1: a = 6.14 x 10^{-6} A/V^2, b = -800 V; I_2: a = 1.37 x 10^{-6} A/V^2, b = -1350 V; F_1: a = 8.29 x 10^{-6} A/V^2, b = -1740 V; F_2: a = 1.12 x 10^{-6} A/V^2, b = -1810 V.

With the roughly 20 sets of cathodes studied to date, we have observed that 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.

Generally, our observations of self-heating substantiate the following. At currents of approximately 200 μA, a reversible change in the cathode's I-V characteristic is observed that is consistent with the thermal desorption of weakly bound surface adsorbents, such as hydrogen, arriving from residual gas atmosphere. For current levels exceeding approximately 400 μA, and often approaching 1 to 3 mA, irreversible changes in the I-V characteristics are observed. These changes are consistent with smoothing of the tip surface via thermally activated, field assisted, surface self-diffusion.

Preliminary field-ion imaging studies of the cathodes also support this conclusion. The result of surface self-diffusion is a significant increase in emitting area on the tip surface, a decrease in emission current noise, surface recrystallization and I-V uniformity enhancement between microfabricated tips.

3.3 High current operation

The maximum repetitively pulsed current from an individual single Spindt tip we have attempted to extract to date is 3.5 mA. The maximum d.c. emission current that we have extracted from a single Spindt tip is ~ 1 mA. Fig. 4 shows the I-V data for a tip operated at 1 mA d.c.. This cathode was operated for 0.5 h at which point the experiment was ended due to concerns over excessive outgassing of the phosphor anode in the field-emission microscope apparatus used for the experiment.

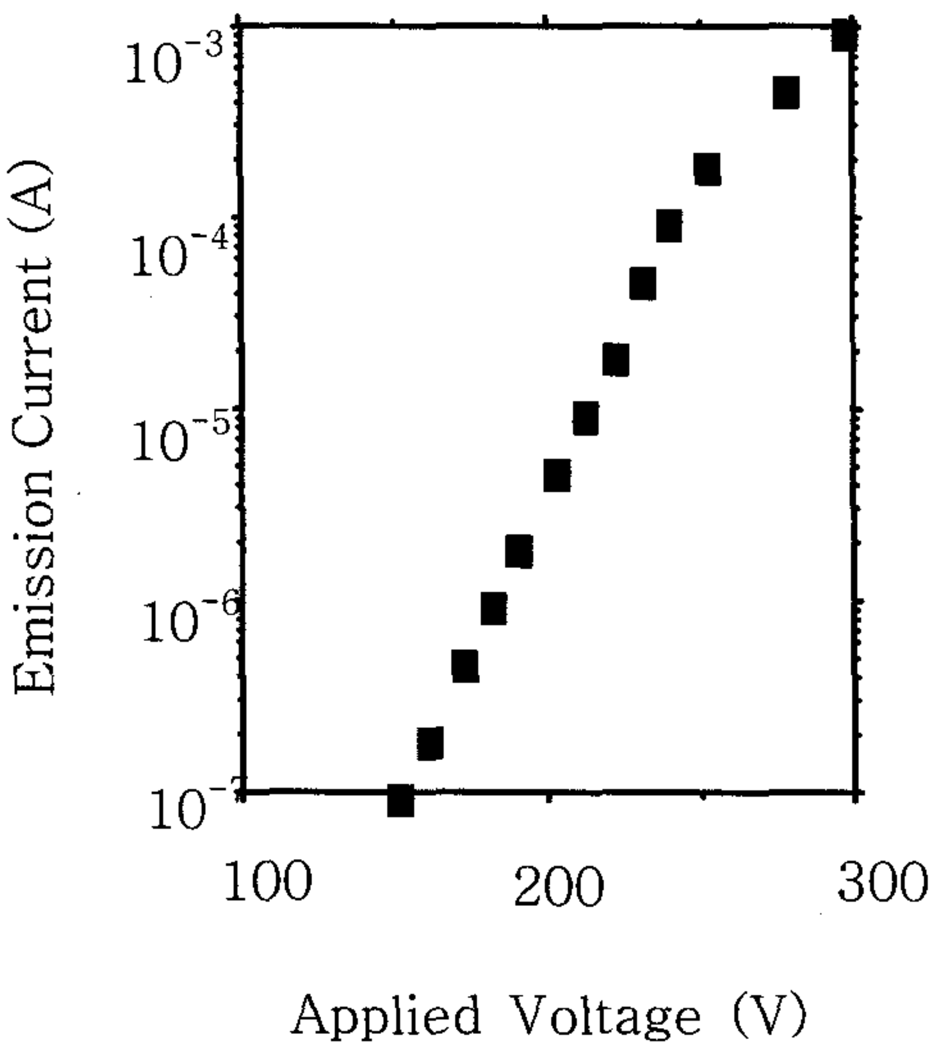

Fig. 4. I-V data from a single tip Spindt cathode at 1 mA d.c. for 1/2 h. FN coefficients: $a = 5.1 \times 10^{-5}$ A/V^2, $b = -2514$ V.

Due to the relatively low applied field used between the cathode and phosphor anode (~ 300 V/cm), space charge effects can be seen as 1 mA of emission current is approached. Prior to operating this cathode at 1 mA d.c., the cathode was pulse conditioned up to a current of ~ 1.2 mA to reform the tip surface and remove contaminants. From this work, it appears that Spindt cathodes can provide very high current per tip loading, limited only by yielding of the tip due to field stress, or by emission current sufficient to initiate a vacuum arc as described by Dyke and Dolan[1].

4. Conclusions

We have found that cathode failures at emission levels in the 10 - 100 μA per tip range have often been due to voltage breakdown associated with thin (< 1 μm) dielectric layers rather than excessive emission from emitter tips. With a dielectric thickness in the 1.5-μm range, emission levels of over 1 mA have been achieved repeatedly from single emitter tips. Furthermore, Spindt cathodes can be annealed and effectively cleaned by Joule heating at these elevated emission levels thereby improving emission stability. In addition, the annealing process can be used to make the I-V characteristics of as fabricated cathodes very similar to one another. Thus the self-heating process can be used to both enhance emission uniformity from arrays and to clean, or reclean, tip surfaces in situ during operation.

References

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