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Microfabricated Field Emitter Arrays

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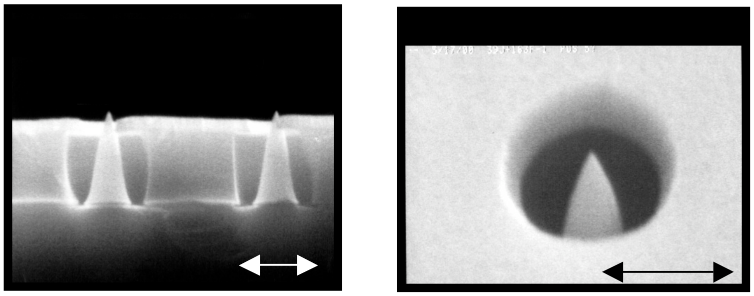
Prof. Erwin Müller's early work with field electron emission microscopy in the 1930s evolved relatively quickly into field ion microscopy and eventually the atom probe in the 1950s. While Prof. Müller and co-workers' interests focused on field ionization as a tool for microscopy and mass analysis, researchers at the Linfield Research Institute noted Prof. Müller's early work and began studying the many interesting features of field electron emission. In the 1950s the Linfield group performed exhaustive studies of etched-wire single-crystal field emitter cathodes and demonstrated enormous current densities from single tips [1]. However, a means of operating many emitter tips in parallel to produce large total cold electron emission currents eluded them, mostly because of unsatisfactory uniformity of emission from tip to tip and mutual electrostatic shielding issues in tightly packed arrays of emitter tips. With the emergence of microfabrication technology beginning in the early 1960s, our group at SRI International conceived the notion of microfabricating field emitter tips and arrays of emitter tips with integrated extraction electrodes using thin-film deposition and patterning techniques of the kind also being developed at that time for solid-state integrated circuits. The purpose was to achieve the high electric fields required with close spacing rather than high voltage, and large currents with many tips operating in parallel. The first results with a random array of micron-sized emitter tips having an integrated extraction electrode, or gate, showing cold field emission of 1.5 μA to a distant anode with only 50 volts applied between tips and gate were published in 1968 [2].

As microfabrication technology evolved, nanolithography tools were developed, and it is now possible to fabricate arrays of 10^8 tips per square centimeter and to produce hundreds of milliamps of emission from 1-mm-diameter arrays of emitter tips. Fig. 1 shows images of typical microfabricated emitters. A great deal of research has been done with single microfabricated emitters to learn the fundamental limits of emission and to study techniques for processing emitters for improved uniformity and stability of emission. Early field emission workers showed that thermal cleaning and forming of etched wire emitters is important to stable emission performance. Unfortunately, the temperatures required (about 2000^{o}C) are not possible with microfabricated structures. However, we have discovered that careful conditioning of single microfabricated molybdenum tips with pulsed emission up to the milliamp level can be used to thermally clean and anneal the tips by Joule heating and thermal self-diffusion [3]. Fig. 2 shows the results of heating and forming single molybdenum tips by pulsing into the milliamp range with 100 μs, 30 Hz pulses. We note that the emission for a given voltage improves after pulsing to about 100 μA, indicating cleaning by desorption, and decreases after pulsing to the 1 mA range due to blunting of the tip by thermal self-diffusion. This technique has been applied to arrays of tips to improve emission uniformity over an array by blunting the overachieving tips, thereby allowing higher total emission currents to be obtained without suffering individual tip failures. Fig. 3 is a voltage current curve showing a peak emission level of 300 mA from a 50,000-tip array covering a 1-mm diameter area (40 A/cm^2). The array is fabricated on a resistive silicon substrate, which effectively places a resistor in series with the emitter tips. The voltage is applied between the gate and the back of the silicon substrate so that the measured voltage includes the drop across the silicon substrate. The actual voltage between the emitter tips and the gate is calculated using the Fowler/Nordheim equation "a" and "b" coefficients ($I = aV^2e^{-b/v}$) extracted from a Fowler/Nordheim plot of the low current emission regime where the silicon resistance is ineffective. Fig. 3 also shows the calculated emission curve using these data [4].



a b

FIG. 1. A cross-section and a top angle view of microfabricated molybdenum field emitter tips on a silicon substrate with an integrated molybdenum gate electrode on an insulating silicon dioxide layer. Scale bar in Fig. 1a = 2 µm and in Fig.1b = 1 µm.

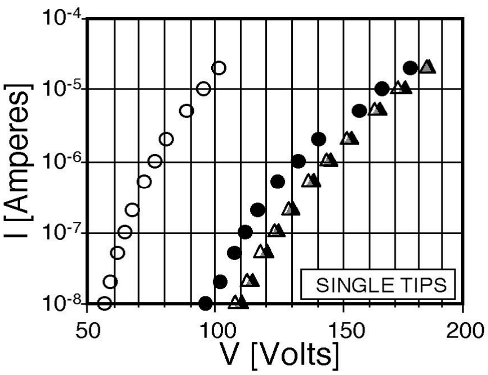


FIG. 2

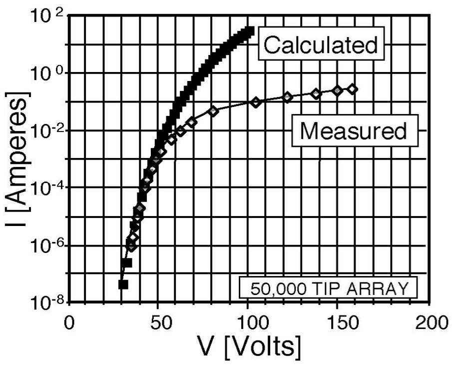


FIG. 3

Figure 2. I-V plots for two very different single tips (circles) as fabricated and after pulsing, while connected in parallel, to 1.5 mA with 100 µs pulses at 30 Hz thereby forming the tips to produce essentially identical emission characteristics (triangles).

Figure 3. A 50,000-tip array pulsed to 300 mA. Roll-off is due to series resistance introduced by the silicon substrate. Calculated curve shows what the emission would be without the series resistance.

References

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