MODELING DEVICE PERFORMANCE AND FEATURE VARIATION IN MICROTIP FIELD EMITTERS

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ABSTRACT

A theoretical model for vacuum field emission that applies to real three-dimensional (3-D) microtip emitters has been developed. This model provides electric field variation along the microtip surface, an analytical solution for current density and a basis for defining the device characteristics, interalia, effective emission area and tip current. The derivation of this model relies on extending the one-dimensional (1-D) planar Fowler-Nordheim (F-N) equation to 3-D microtips and modeling the geometry in prolate spheroidal coordinates. This coordinate system's unique alignment with the microtip geometry offers an unexpected analytical simplicity. In developing this model, the exact solution for the electric field at the microtip/base junction given by the prolate spheroidal model is substituted into the F-N equation, yielding an analytical expression that describes tunnel current density (Figure 1). Total tip current (Figure 2) is obtained by integration over the tip surface. This model provides an analytical definition for the often-reported experimental enhancement factor β, clarifying its variation with microtip sharpness while corroborating its geometry dependence. For the tip parameters depicted in Figures 1 and 2, the results show that 99.9% of the tip current is due to the area between the tip apex and ξ=1.007.

This theoretical model provides the framework for addressing the observed variation in microtip current that is due to variability in the fabrication process of field emitter arrays (FEA). These process variations significantly affect the operating characteristics of vacuum field emitter devices. Array current and frequency response for the device can be analyzed by treating the local tip radius as a random variable and using a probabilistic model to provide expected value current for a microtip array. The results of these statistical analyses highlight the importance of tip radius uniformity in FEA operation and demonstrate its quantitative effect. Our studies elucidate the dominance of the sharpest tips in an array by using examples of arrays with Gaussian and Rayleigh tip radius probability density functions (Figure 3). Our studies reveal an analytical basis for which the Rayleigh pdf may be a good model for the real tip radius variation. Some expected values for FEA current are tabulated for a variety of statistical parameters to provide comparison with experimental data (Table 1). The analysis illustrates the difficulty in predicting the performance of an FEA based on the measured emission characteristics of a single tip. The nonlinear dependence of array current on tip radius variation shows that the electron beam characteristics are dictated by the dominant emitters, which may be few in number. The understanding and quantification of both the statistical effects of tip radius variation and the geometrical characterization of individual tips are critical to device modeling where emission characteristics are paramount (e.g., vacuum electronics), and can assist in developing a device testing strategy to support fabrication specifications.

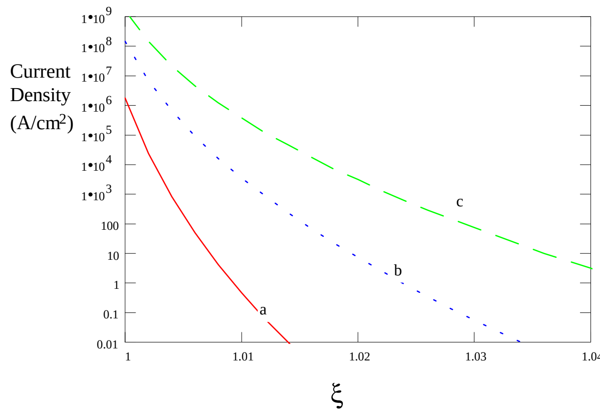

Figure 1. Current density vs. ξ for a prolate spheroidal tip. d = 10000 Å, a = 10025 Å, Φ =4.7 eV, and voltages (a) V = 100 volts, (b) V = 150 volts, (c) V = 200 volts.

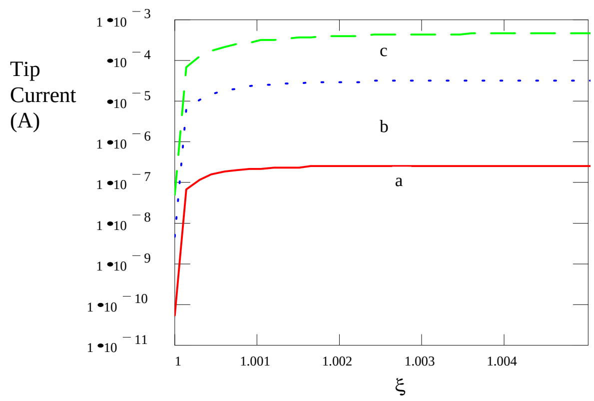

Figure 2. Cumulative Tip current vs. ξ for a prolate spheroidal tip. d = 10000 Å, a = 10025 Å, Φ= 4.7 eV, and voltages (a) V = 100 volts, (b) V = 150 volts, (c) V = 200 volts.

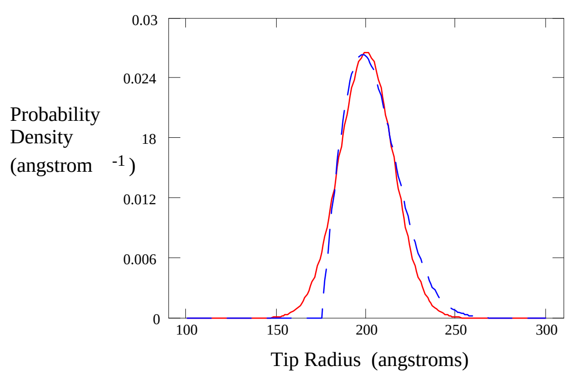

Figure 3. Comparison of Gaussian & Rayleigh pdf for tip radii 100-300 Å. Gaussian (μ=200 Å, σ=15 Å, solid). Rayleigh (γ=175 Å, λ=23 Å, dashed).

Gaussian			Rayleigh		
mean μ	std dev σ	tip current exp value	γ	λ	tip current exp value
50	5	48 mA.	41	7.6	46 mA.
50	10	55 mA.	34	15	46 mA.
50	15	57 mA.	25	23	53 mA.
100	10	2 mA.	84	15	1 mA.
100	20	3 mA.	67	30	2 mA.
100	30	4 mA.	51	45	3 mA.
200	20	3.2 μA.	167	30	1.7 μA.
200	40	20.6 μA.	134	61	5.5 μA.
200	60	37.6 μA.	104	91	21.9 μA.
400	40	1.54 nA.	334	61	.004 nA.
400	80	6.31 nA.	268	121	.119 nA.
400	120	16.44 nA.	208	185	3.6 nA.

Table 1. Tip Current Expected Value for Gaussian & Rayleigh pdf with tip radius distributions as indicated.

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