New Current-Voltage Model for Statistically Distributed Field Emitters

Myoung-Bok Lee[1], Jae-Hoon Lee, Ki-Rock Kwon, Sung-Ho Hahm, Jong-Hyun Lee, and Jung-Hee Lee
School of Electronic and Electrical Engineering, Kyungpook National University, Taegu, 702-701, Korea
Tel: +82-53-950-6431, E-mail: mblee@ee.knu.ac.kr

ABSTRACT

For the I-V modeling of sharp tip arrays and nanostructured planar emitters, we propose a new and much practical I-V relation including tip height and radius by considering a statistical distribution of tip radius. Frequently observed nonlinearity of Fowler-Nordheim plot for sharp tip and tip arrays was successfully simulated and then, an application example was provided to extract relevant emission-governing parameters of sharp tip.

1. INTRODUCTION

Various types of field emitting devices were proposed and tested for relevant applications: sharp metallic or semiconducting tip array is one class and planar surface is another class. Field emission behavior, emission current density (J; A/cm^2) versus applied field (F; V/cm), of smooth surface was predicted by Fowler-Nordheim model as follows [1];

$$J = A\frac{F^2}{\phi}\exp\left(-\frac{B\phi^{3/2}}{F}\right) \qquad (1)$$

where ϕ is the barrier height for the emitter surface in eV, A=1.56x10^{-6} and B=6.83x10^7. In addition to smooth surface, this simple relation was successful, to some extent, for the qualitative description of sharp tips by considering an effective emission area, α in cm^2 and field enhancement factor, β. From the measured emission current versus voltage applied between the cathode and anode, one can extract key emission-governing parameters, such as emission area, surface barrier height, and field enhancement factor via the linear Fowler-Nordheim (FN) plot. However, the FN plot of measured current-voltage (I-V) data was not generally linear especially for sharp tip arrays and nanostructured thin films due to non-uniformity of emission sites as recently reported by Cui *et al.* [2]. Until now, many interesting and more general I-V relations have been suggested by considering a statistical distribution of emission sites, such as tip radius and tip height in order to model the nonlinearity of FN plot [2-4]. However, neither of them were emitter-structure dependent nor analytical and applicable to find detailed origin for the change of emission parameters such as emission site density, average radius of emission sites, and surface workfunction. In this work, we are going to propose a new but much practical I-V relation of a field emission device with a Gaussian distribution (GD) of nanostructured emitter radius. Application work is being done to evaluate the characteristics of fabricated emission devices.

2. THEORETICAL MODEL

On the basis of ideal field emitter with floating sphere, emission I-V relation of single sphere with radius *R* (cm) and height *h* (cm) can be expressed in a simplified form by considering both the FN model (Eq.1) as an ideal emission relation and the effective field as a peak value on the floating sphere [5];

$$F = \frac{V}{d}\left(\frac{h}{R}+3\right) \qquad (2)$$

where d (cm) is the spacing between the planes and V is the applied voltage in volt. A tip parameter-dependent I-V relation per emission site was calculated by Nicolaescu to be as follow [4];

$$I_c = 4\pi\left(\frac{h}{d}\right)^2 A_1(\phi)V^2\exp\left[-\frac{E_c(\phi)dR}{Vh}\right] \qquad (3)$$

where $A_1(\phi)$ and $E_c(\phi)$ are barrier height dependent constants. If the tip has single emission site with the corresponding structural parameters, the field emission behavior would be well matched with the linear FN plot as expressed in Eq. (3). Instead, since the planar surface or tip arrays have generally multiple emission sites revealing a statistical distribution of tip height and radius [2-5], one must integrate each current contribution of specific emission site to obtain more universal I-V relation. For this purpose, the GD was normally assumed and proved to be most appropriate for the I-V modeling of nanostructured planar emitters. From the previous study [4], the statistical distribution of tip radius was turned out to be mainly responsible for the nonlinearity of FN plot instead of the normal distribution of tip height. But, no analytical I-V relation was obtained on the GD of emission site tip radius.

Here, we report an analytical I-V relation by considering a GD of tip radius:

$$G(R) = G_0 \exp\left(- \frac{(R - R_0)^2}{2\sigma_R{}^2} \right) \qquad (4)$$

where R_0 is average tip radius and σ_R the standard deviation of tip radius. The integral of Eq. (4) for two limited radius values should be the number (N) of total emission sites.

$$N = \int_{0_1}^{R_{\max}} G(R)dR \approx \sqrt{\frac{\pi}{2}}\sigma_R G_0 \qquad (5)$$

The two limits of tip radius were assumed to be 0 and $R_{\max}$. Then, by using the I-V relation of Eq. (3), the total sum of average current per emission site can be defined as follows;

$$I = N\bar{I} = \int_0^{R_{\max}} I_c G(R)dR \qquad (6)$$

The above integral results in a complicated relation of I-V including error functions but can be simplified as follows for the $R_{\max} \geq R_0$:

$$I \approx 4\pi^2\sigma_R{}^2 G_0{}^2\left(\frac{h}{d}\right)^2 A_1(\phi)V^2$$
$$\times \exp\left[- \frac{E_c(\phi)(d/h)(-E_c(\phi)(d/h)\cdot\sigma_R{}^2 + 2R_0\cdot V)}{2V^2} \right] \qquad (7)$$

The 1st term of exponential is newly introduced and nonlinear for the FN plot due to the statistical distribution of emission site tip radius. The 2nd term is due to an ideal emission of electrons through the potential barrier as predicted in Eq. (3). This is a new and much practical I-V relation applicable to the field emission of sharp tip or tip arrays including nanostructured planar emission devices such as amorphous carbon and carbon nanotubes.

3. SIMULATION OF MEASURED I-V DATA

Fig. 1 shows a series of the measured I-V data from a sharp poly-Si field emitter with the progress of activation cycle from the initial state. Detailed fabrication and activation conditions were previously reported [6-7]. The FN plot of ln(I/V^2) versus 1/V is demonstrated in fig.2 with the best fittings by the FN model (dashed straight line) and this model (solid curved line). As compared, a distinctive nonlinear FN plot was observed for the sharp emitter and only our model was applicable to the interpretation of the experimental field emission behavior. Many other experimental results also indicated a similar trend especially for the amorphous carbon films with nanostructured emission sites.

4. CONCLUSIONS

A new analytical I-V relation was derived and tested to simulate the nonlinearity of FN plot for the sharp tip and planar emitters such as amorphous carbon and carbon nanotubes.

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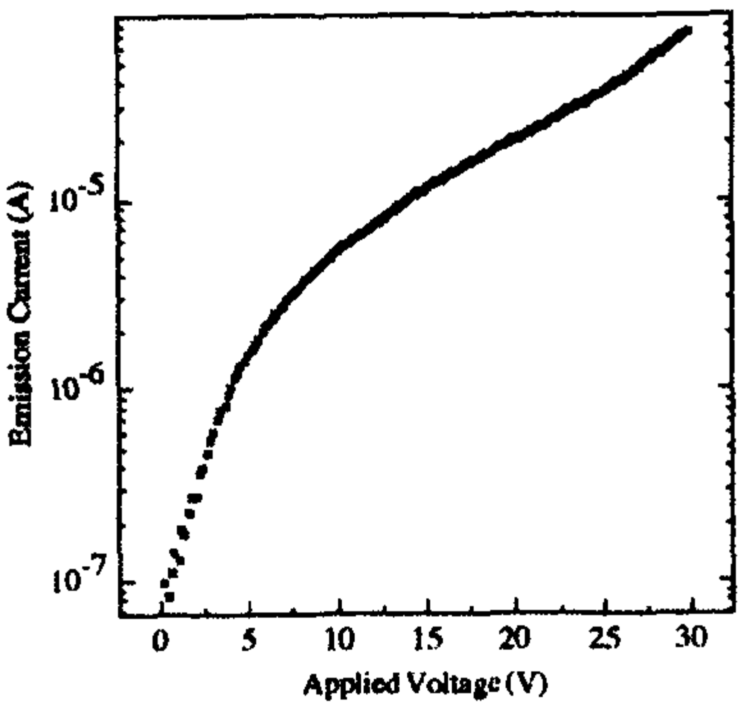

Fig.1. Example of field emission I-V data measured from a sharp poly-Si emitter [6].

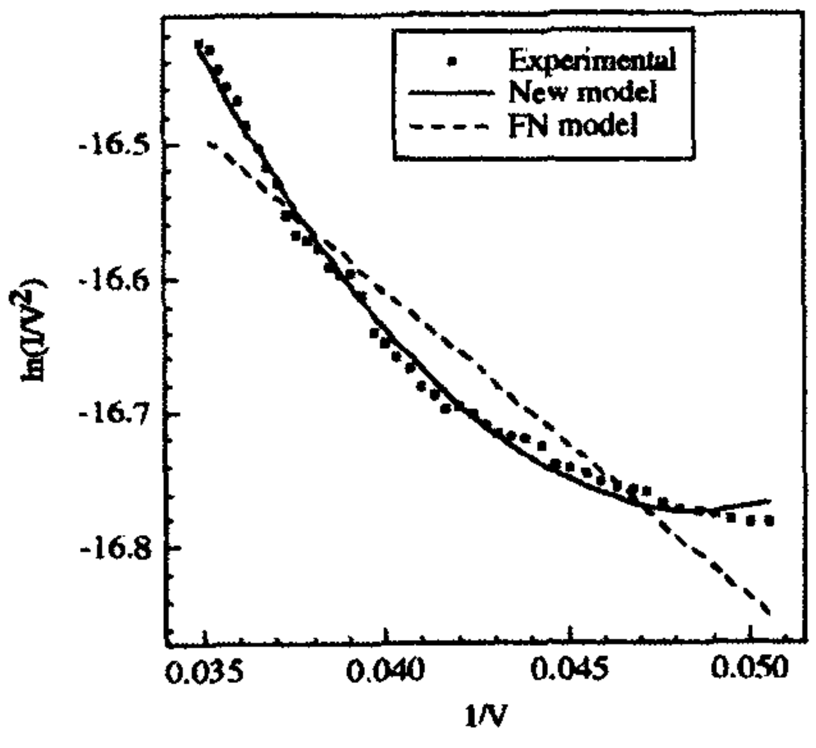

Fig.2. Best fitting of FN plot for measured I-V data of fig.1 by FN model (dashed line) and this model (solid line).