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Field electron emission area revisited: an integrated method for the area extraction model

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Abstract: For electron field emitters, the emitter's physical and geometrical parameters, namely the emitter work function and its geometrical factor, are extracted from the slope of the Fowler–Nordheim (FN) plot. The literature contains few investigations and reviews of extended parameter extraction models based on the slope and intercept of the FN plot. However, due to the complexity of these reviews, there is a great need for an integrated approach to the area extraction model whereby a simplified account of the derivation and implementation of the model is presented and made convenient, especially for scholars other than physicists and engineers. This is precisely the aim of the present article, where the standard FN equation and Schottky–Nordheim barrier functions are preserved and only measurable parameters are involved in the extraction model and the derivation of the area extraction equation. In addition, the model is applied to experimental field emission data from a single LaB_6 nanoemitter to support the discussion and to elaborate on the model's applicability, significance, and advantages.

Key words: Field electron emission, Fowler–Nordheim theory, Fowler–Nordheim equation, emission area, parameter extraction model

1. Introduction

Analysis of experimental field electron emission data (namely current–voltage data) is based on a qualitative assessment of Fowler–Nordheim (FN) plot behavior and extraction of the emitter's physical and geometrical parameters, namely the emitter work function and its geometrical enhancement factor from the slope of the FN plot (generally the plot of $\ln(I/V^2)$ versus $1 / V$) [1–4]. For a single emitter of spherical tip, the emission area is usually determined from the geometrical enhancement factor assuming a homogeneous and constant field at the emitter surface. When emission occurs from many emitters, as in field emission arrays, the situation becomes more complicated and researchers tend to measure the substrate area instead of the actual emission area [5–8]. In either case, this may cause an imprecise determination of emission current density and may lead to inaccurate interpretations of the experimental data. There is therefore a great need to determine the emission area more accurately from the FN plot.

The literature contains few investigations of extended parameter extraction models based on slope and intercept of the FN plot. Works by Charbonnier and Martin in 1962 [9], Forbes in 1999 [10], and Forbes et al. in 2004 and 2013 [11,12] are the most important and interesting achievements in this regard, where an area extraction function was derived from the preexponential term of the FN equation. In addition, effects such as the shape of the surface potential barrier on the parameter extraction model have been investigated satisfactorily

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[12]. However, there is still a great need for an integrated guide to the area extraction model whereby a simplified account of the derivation and implementation of the model is presented and made convenient, especially for scholars other than physicists and engineers. This is precisely the aim of the present article, where the form of the standard FN equation and Schottky–Nordheim barrier functions are preserved and only measurable parameters are involved in the extraction model and the derivation of the area extraction equation. In addition, the model is applied to experimental field emission data from a single LaB_6 nanoemitter to support the discussion and to elaborate on the model's applicability, significance, and advantages.

2. Theoretical background

2.1. Area extraction model

Field electron emission current is defined by the conventional FN equation [13]:

$$I = \frac{aF_a^2 A}{\varphi_{eff.}\ t^2(y)} \exp\left[\frac{-\upsilon\,(y)\,b\varphi_{eff.}^{3/2}}{F_a}\right], \tag{1}$$

where $a = e^3 \big/ (8\pi h_P) = 1.541434 \times 10^{-6}$ (A eV V^{-2}), $b = (8\pi\,/\,3)\,(2m_e)^{1/2} \Big/ (eh_P) = 6.830890$ ($\mathrm{eV}^{3/2}$ V nm^{-1}), $t(y)$ is a slowly varying function, and $\upsilon(y)$ is a correction function due to image force approximation (both are known as Schottky–Nordheim barrier functions).

$$F_a = \beta V \tag{2}$$

β is the geometrical enhancement factor and V is the applied voltage between the emitter and the counter electrode. By taking ln of both sides of Eq. (1), the FN equation can be written as follows:

$$\ln\frac{I}{V^2} = \frac{-6.83089\ \varphi^{1.5}\upsilon(y)}{\beta V} + \ln\left[\frac{1.541434\ \times\ 10^{-6}\ \beta^2\ A}{\varphi t^2(y)}\right]. \tag{3}$$

Eq. (3) is a straight line equation and the FN plot is expressed as $\ln(I/V^2)$ versus $(1\ /\ V)$. The voltage is measured in volts, while current is measured in amperes. The slope, which is known as the FN slope (S_{FN}), is equal to

$$S_{FN} = \frac{-6.83089\ \ \varphi^{1.5}\,\upsilon(y)}{\beta}, \tag{4}$$

while the intercept ($Int._{FN}$) of the straight line is the second term of the right-hand side of Eq. (3):

$$Int._{FN} = \ln\left[\frac{1.541434\ \times\ 10^{-6}\ \ \beta^2\ A}{\varphi t^2(y)}\right]. \tag{5}$$

Substituting β from Eq. (4) into Eq. (5) and rearranging for emission area (A), one gets the following equation:

$$A = \frac{13903.4189\ \ S_{FN}^{\,2}\ \ \exp\left(Int._{FN}\right)\ \ t^2(y)}{\varphi^2\ \ \upsilon^2(y)}. \tag{6}$$

Eq. (6) is the actual emission area in nm^2, which differs from the emitter geometrical area usually estimated from the dimensions of the substrate.

2.2. Implementation of Eq. (6) for field emission data from a LaB_6 emitter

The field electron emission current is measured from a thick LaB_6 layer deposited on a tungsten microneedle under ultrahigh vacuum conditions ($< 5 \times 10^{-9}$ mbar). Details of sample preparation were presented by Late et al. [14]. The surface morphology, investigated under a scanning electron microscope (JEOL 6360A; JEOL, Peabody, MA, USA), confirms that protrusions of less than 1 μm exist at the emitter apex (inset of Figure 1a). Electron emission from these protrusions is anticipated due to field enhancement. The FN plot (Figure 1b), derived from the field emission I-V data, shows linear characteristics signifying field emission from metallic material.

The actual emission area (A), determined from Eq. (6) by substituting the slope and intercept values from the best fit of the FN plot (i.e. $S_{FN} = -41693$, $Int._{FN} = -18.899$), is $2.216 \times 10^4 \frac{t^2(y)}{v^2(y)}$ nm^2. The radius (r) of the emitting surface is equal to 59.7 $\frac{t}{v}$ nm.

2.3. Substitution of $\frac{t^2}{v^2}$ ratio

In order to substitute the ratio $\frac{t^2}{v^2}$, the macroscopic field value and work function need to be known, because this ratio varies with the applied field and the work function of the emitter [15]. An iterative method to find the correct $\frac{t^2}{v^2}$ ratio takes the following steps (Figure 2):

1. Initially, take $\frac{t^2}{v^2}$ equal to 1; determine the area in nm^2 (i.e. from $2.216 \times 10^4 \frac{t^2(y)}{v^2(y)}$ in the present emitter).

2. Calculate the radius (r) of the emitter, where $r = \sqrt{A/2\pi}$.

3. Assuming $F = \frac{V}{\alpha r}$, where $\alpha = 5$ for spherical emitter, calculate F at a given voltage value.

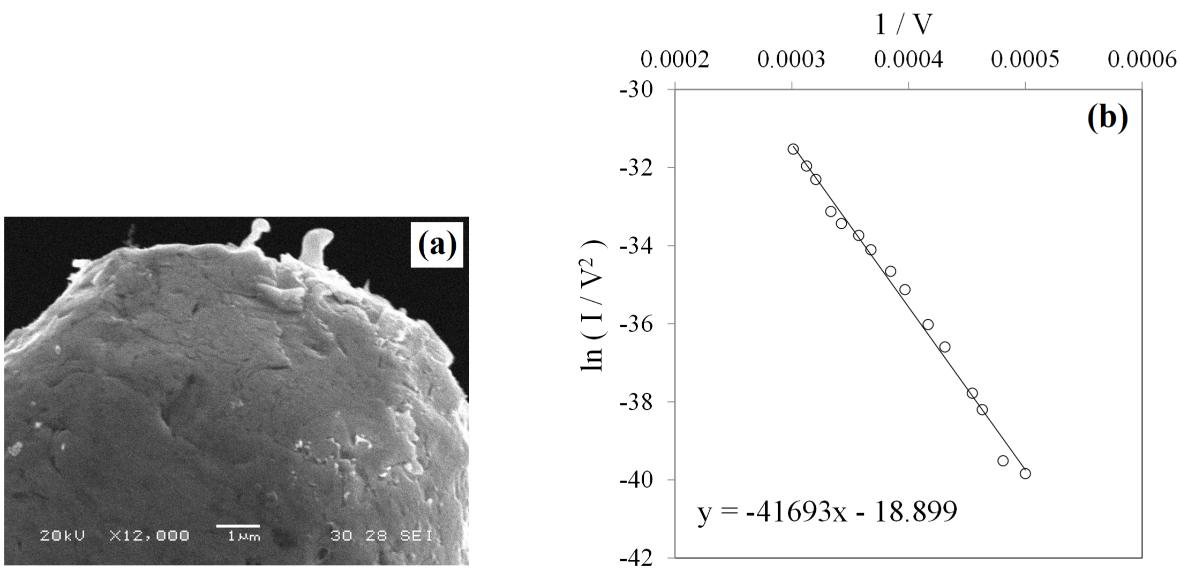

Figure 1. a) Protrusions of LaB_6 deposited on tungsten tip. b) Experimental Fowler–Nordheim plot obtained from the LaB_6/W emitter.

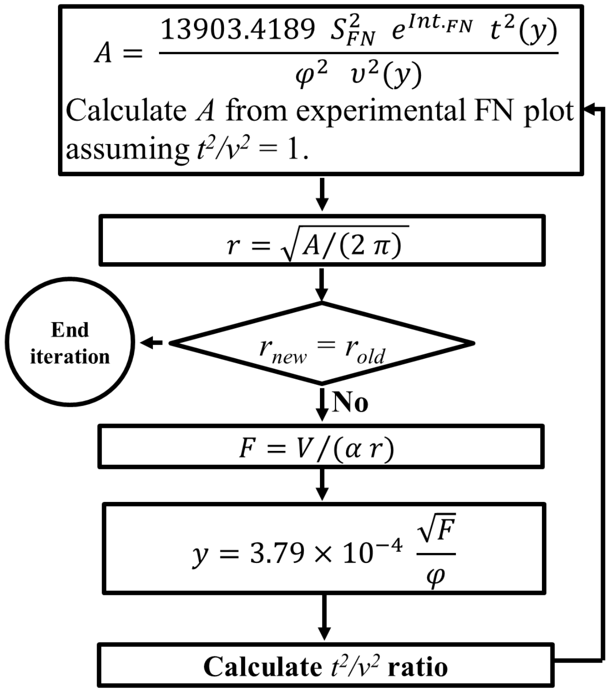

Figure 2. Flowchart of iteration method used to determine the $\frac{t^2}{v^2}$ ratio.

4. $y = 3.79 \times 10^{-4} \frac{\sqrt{F}}{\varphi}$, where F is in units of V/cm.

5. Calculate a new value of the ratio $\frac{t^2}{v^2}$ from y. Substitute this ratio to calculate a corrected area.

6. Repeat Steps 1–4 until a constant area value is being determined consecutively from the iterations.

The actual emission area and radius at applied voltage of 500 V are 4.5505 $\times$ 10^4 nm^2 and 85 nm, respectively. Figure 3 shows the convergence of the iteration method to the final value of the actual emission area.

3. Discussion

The significance of Eq. (6) can be summarized as follows

1. Eq. (6) calculates the actual emitting area, which differs from the emitter geometrical area.

2. The geometrical enhancement factor does not appear in Eq. (6). There is, therefore, no need to calculate this factor or search for an approximation of its value.

3. The emitter radius can be determined from the actual emitting area assuming a hemispherical emitter apex.

4. Eq. (6) results in an emission area that depends on the applied voltage. Calculations showed that the iteration method of the emission area resulted in area values that increased linearly with the voltage value taken into consideration (i.e. in calculating the ratio $\frac{t^2}{v^2}$). This is shown in Figure 4 for the LaB_6 emitter. The Table shows the numerical values of the actual emission area calculated using Eq. (6) via the iterative method and the dependence of area on the applied voltage. Results show that area increases two times when applied voltage is raised from 600 V to 1.4 kV.

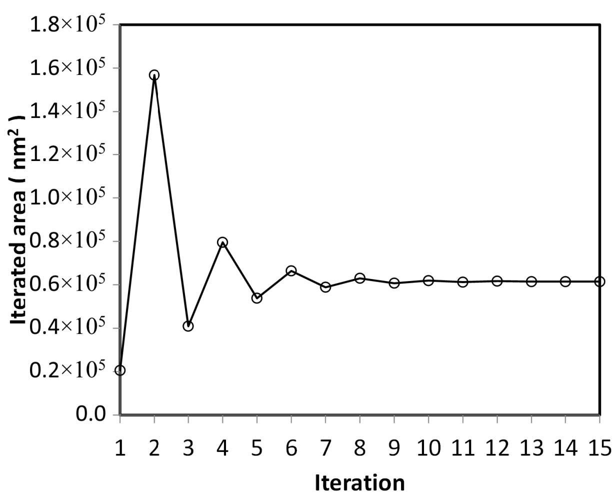

Figure 3. Convergence of the iteration results of the actual emission area.

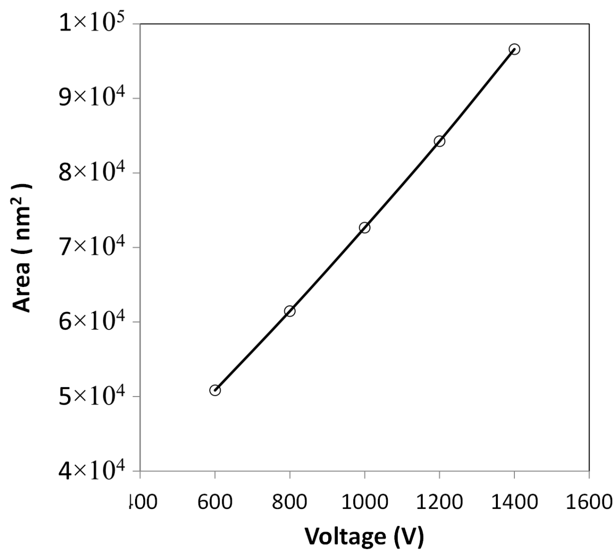

Figure 4. Dependence of the actual emission area on applied voltage.

Table. The dependence of the actual emission area on the applied voltage.

Voltage (V)	t^2/v^2	r (nm)	A (nm^2)
600	2.465	89.9	5.0836×10^4
800	2.991	98.9	6.1466×10^4
1000	3.536	107.7	7.2958×10^4
1200	4.161	115.8	8.4257×10^4
1400	4.701	125.3	9.8679×10^4

4. Conclusions

Field emission was recorded from a LaB_6 emitter. An area extraction equation was derived from the slope and the intercept of the FN equation, presented in a simple, nontrivial fashion, and used along with an iterative method for determination of the actual emission area from experimental data. The significance of the area extraction equation in determining the actual emission area was highlighted. The area extraction equation can be presented and used in a simple, nontrivial fashion convenient for scholars who are not physicists or engineers.

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