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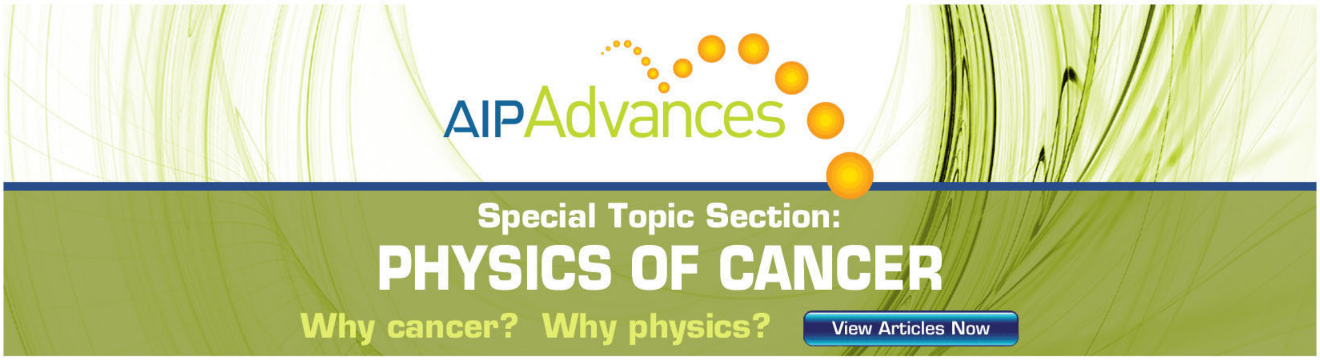

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Response to "Comment on 'Model calculation for enhancement factor of a gated field emission nanotube' " [J. Appl. Phys. 104, 116103 (2008)]

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The response addressed the comments of Roumeliotis and Xanthakis on our article [J. Appl. Phys. **102**, 114503 (2007)]. The experimental results showed that the choice of the nanotube shape was true. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3035972]

In a recent article,[1] we calculated the enhancement factor of a gated field emission nanotube (NT). According to their model and results in their comment, Roumeliotis and Xanthakis[2] expressed their different views on the calculation reported by us.[1] Our responses to their specific points are as follows.

(1) They suggested "Due to the above truncations only a small number of expansion coefficients …."

The electric potential must be a solution of Laplace's equation (1), hence Eq. (11) could be rewritten as

$$\Phi(z,r) = \Psi_1(z) \times \Psi_2(r), \tag{1}$$

where $\Psi_1(z)$ and $\Psi_2(r)$ are functions of z and r, respectively. From Eq. (4), it could be seen that the function $\Psi_2(r)$ was the linear superposition of both Bessel $J_0(k'r)$ and Neumann $N_0(k'r)$ functions in the region of $k'>0$, i.e., $\Psi_2(r) = CJ_0(k'r)+DN_0(k'r)$, where k', C, and D are constants. Based on the boundary condition $\Phi|_{r=r_0}=0$, the function above could be written as $\Psi_2(r)=C'\times[J_0(k'r) - J_0(k'r_0)N_0(k'r)/N_0(k'r_0)]$. Thus, the function $\Phi(L,r)$ could be expressed by

$$\Phi(L,r) = U_m \times [J_0(k'r) - J_0(k'r_0)N_0(k'r)/N_0(k'r_0)], \tag{2}$$

where C' and U_m are coefficients. If assuming $k'=k_1$, the following equations $A_1''=U_m/sh(k_1L)$, $A_i''=0$ $(i=2,3,4,\ldots)$ could be obtained from Eq. (2) and Eq. (11) at $z=L$; hence the electric potential near the NT side could be expressed by Eq. (12). Similarly, the potential over the NT top could be expressed by Eq. (8) in our paper.

To calculate the field enhancement factor, we only need to calculate the local electric field near the surface of the NT in our work. Therefore, it was not necessary to consider the potential distribution in the region of $r>R$ because the gate hole radius was much larger than NT radii r_0. Equations (8) and (12) only expressed the potential distribution near the axis z, and the electric fields were mainly calculated in the region of $r\leq R$. Furthermore, the equation

$$\left[V_a - \frac{(V_a-V_g)J_0(k_1r_0) - V_aJ_0(k_1R)}{J_0(k_1r_0)-J_0(k_1R)}\right]\left[1-\frac{J_0(k_1r)}{J_0(k_0r_0)}\right] = U_m\left[J_0(k_1r) - \frac{J_0(k_1r_0)N_0(k_1r)}{N_0(k_1r_0)}\right]$$

could be obtained from the boundary condition in which the potential must be continuous everywhere at the interface in the region of $r_0\leq r\leq R$. The potential expressed in Eq. (8) would be equal to Eq. (12) when considering the above equation to our calculation at $z=d_1$ and $r_0\leq r\leq R$.

(2) They asked "what is the physical significance of the β they calculated when the applied field is in the vertical z direction …" and persuaded "The E_r of the lower region that the authors have used in the calculation of β is totally irrelevant to the formation of the tunneling barrier as this is always on the top of a NT …."

The β in our paper could be expressed as the field enhancement factor of NT top edge. In F-N theory, the field enhancement factor was defined by $\beta=|E_a|/|E_m|$,[3] where E_a was the actual electric field on the effective emission area of the NT and E_m was the macroscopic applied electric field. In our model, it was considered that the top of the open NT's wall was flat based on the experimental results,[4–6] i.e., the top curvature of the NT's wall was zero as shown in Fig. 1. Therefore, the NT top edge was mainly operated as the effective emission area and the absolute value of actual electric field on the top edge of NT was expressed by $|E_a| = \sqrt{E_z^2+E_r^2}$, where E_z and E_r were the electric field intensities in the axial and radial directions at $z=L$, $r=r_0$, respectively. The field in the z direction is very weak on the top of NT,

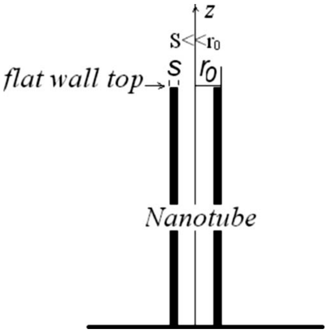

FIG. 1. Schematic illustration of open NT.

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compared with the electric field in the radial directions on the top edge of NT (i.e., $E_z \ll E_r$ on the top edge of NT in this case), so the absolute value of actual electric field $|E_a|$ on the top edge of NT could be expressed by $|E_r|$.

In our model, the effective emission area was the top edge of NT, the formation of the electron tunneling barrier was not on the top of NT but occurred on the top edge of NT. Hence, the enhancement factor β was strictly related to E_r. The electron emission angle on the top edge of NT was not considered in our work and could be derived from E_r/E_z.

(3) They also asked "No particular explanation is given as to why the set (E_z, E_r) of the upper region is not used to calculate β. However …."

Our calculation result showed that the electric field E_z on the top of NT in the region of $r \leq r_0, L \leq z$ was very small compared with E_r on the edge of NT top. To simplify, E_z could be neglected, assuming that the magnitude of actual electric field was approximately equal to E_r. The calculation error was less than 0.0001% in this case. For example, the calculation results showed that the field intensity of NT flat top was $E_z = 4.2056 \times 10^2$ V/μm, the field intensity of NT top side was $E_r = 1.7034 \times 10^6$ V/μm at $L = 10$ μm, $R = 5$ μm, $r_0 = 20$ nm, $d_2 = 200$ μm, $V_a = 1000$ V, and $V_g = 100$ V. Hence, the approximate calculation results were reasonable to explain β.

In the reports of Kokkorakis and co-workers,[7,8] they assumed that the cross section of the wall top of open NT was not flat but a hemisphere. Hence they obtained that the electric field and β depended critically on the radius of the NT top surface and the wall thickness. However, in our paper, the NT wall top was flat and the emitting area was on the NT top edge, so we obtained the different results from theirs, where β did not depend on the top curvatures and wall thickness but was related to NT radii r_0.

Furthermore, we disagreed with their parlances: "it is these unrealistic choices for the shape of the NT and the wrong choice of electric field …." The wall's top of open double-wall or multiwall NT could be considered as flat top.[4–6] For single-wall NT, it is no significance to consider the curvature of single atom on single-wall NT top. Also wall's thickness S is much smaller than r_0 shown in Fig. 1, and this assumption is reasonable to calculate the β. The effect of gate hole radius and gate voltage on the actual electric field around NT was very strong. Thus β was high in our model. The behavior of enhancement factor showed in Fig. 4 (Ref. 1) was in agreement with the practice.

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