JVSTB
Journal of Vacuum Science & Technology B

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Citation: Journal of Vacuum Science & Technology B **22**, 1244 (2004); doi: 10.1116/1.1710488
View online: http://dx.doi.org/10.1116/1.1710488
View Table of Contents: http://scitation.aip.org/content/avs/journal/jvstb/22/3?ver=pdfcov
Published by the AVS: Science & Technology of Materials, Interfaces, and Processing

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Simulation study of carbon nanotube field emission display with under-gate and planar-gate structures

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(Received 6 October 2003; accepted 23 February 2004; published 1 June 2004)

Recently, two new CNTs-based triode structures, i.e., under-gate and planar-gate structures, for field emission display were proposed and exhibited good characteristics. In this paper, we will investigate how the current density distributed on anode plate and how the display's resolution affected by the bias conditions of the emitter and the gate electrode via computer simulation. Our simulation results exhibit that the gate voltage has a strong effect on display's resolution. For the planar triode structure, the good resolution is achieved when the gate voltage is adjusted to converge the electron beams on an anode plate. For the under-gate structure, the display has a good resolution provided that the gate voltage is not too large to pull the electrons striking on other pixels. In general, the under-gate structure has a wider gate-biased operating condition, but the planar triode structure has a higher light efficiency under the same resolution. Due to the lack of field effect in the y-direction, the spot size of the current density on anode plate looks like strips instead of points. And the resolution of the display will be affected by this factor. © *2004 American Vacuum Society.*
[DOI: 10.1116/1.1710488]

I. INTRODUCTION

The discovery of carbon nanotubes (CNTs) has drawn a lot of attention due to their unique physical properties and various potential applications.[1–5] Due to their high aspect ratios and small radii of curvature, CNTs exhibit excellent field emission characteristics. A high field emission current density of 10 mA/cm^2 and low turn-on electric field of 0.75–0.8 V/μm have been reported,[6,7] which are very advantageous for flat panel display applications. In field emission display (FED) design, the triode structures are more attractive for their lower driving voltage and higher light efficiency. Recently, two new CNTs-based triode structures, i.e., under-gate[8] and planar-gate[9] structures, for FEDs were proposed and exhibited good characteristics. In such types of FEDs, the lateral gate electrode generates the transverse electric fields to pull out the electrons from the neighboring emitters. And for the planar-gate structure, the electron beams emitting from the edges of two neighboring emitters can converge on an anode plate to improve the resolution of the display under some bias conditions of the gate electrode. In this paper, the computer simulation studies of such triode-structure CNT-FEDs were carried out to investigate the effects of the gate voltage upon the current density distribution and the convergence of the electron beams on an anode plate.

The simulation model and method is described in Sec. II of this article. In Sec. III, the simulation results and discussions are given. Finally, the conclusions are given in Sec. IV.

II. SIMULATION METHOD

A particle-in-cell computer simulation code MAGIC (Ref. 10) was used for this study. MAGIC is a three-dimensional,

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[a)] Electronic mail: lanyc@mail.ncku.edu.tw finite-difference, time domain code for self-consistent simulation of the electromagnetic fields and charged particles. The electromagnetic fields are advanced in time at each time step. In each time step, the charged particles are moved according to the Lorentz equation using the fields advanced in each time step. The weighted charge density and current density at the grids are subsequently calculated. The obtained charge density and current density are subsequently used as sources in the Maxwell equations for advancing the electromagnetic fields.

In the field emission process, electron emission is modeled by the Fowler–Nordheim (F–N) equation as

$$J=\frac{AE^2}{\phi t^2}\exp\left(\frac{-Bv(y)\phi^{3/2}}{E}\right), \tag{1}$$

where $A=1.5415\times 10^{-6}$, E is the normal component of the electric field at the emitter surface, ϕ is the work function of the emitter, $B=6.8308\times 10^{9}$, t^2 is taken as approximately 1.1, and $v(y)=0.95-y^2$ with $y=3.79\times 10^{-5}\times E^{1/2}/\phi$ in SI units. The MAGIC code provides a F–N equation module to simulate the field emission. Initially, the electrostatic field along the emitter surface is determined for a given geometry and applied voltages. The emission charge is determined by Eq. (1) according to the local electric field. The simulation proceeds by pushing the emitted electrons, weighting the current and charge densities to the grids, updating the electromagnetic fields, and calculating the emission charges. These processes are repeated for each time step until the specified number of time steps is reached. The space-charge effects are automatically included in such a simulation algorithm.

The configurations of under-gate and planar-gate type FEDs investigated in this study are shown in Fig. 1. The Cartesian $x-y-z$ coordinate system is adopted in this simulation study. The simulation domain and the geometry parameters are shown in Fig. 2. Due to the extremely small dimension of the carbon nanotubes, it is impractical to precisely model every nanotube in the whole display structure. Instead, we model the emitter as a thin film electrode and adjust the work function of the artificial emitter to approximate the real nanotube emission current. In our study, the voltage difference between cathode and anode is set to 2000 V. The voltage differences between cathode and gate are set to 30 V, 90 V, 150 V, and 210 V. And the value of the work function used in the simulation is set to 0.095 eV.

III. RESULTS AND DISCUSSIONS

For illustrating clearly the effects of the gate voltage upon the current density distribution and the convergence of the electron beams on anode plate, we compare the simulation results of the electron trajectories, the current distributions on anode plate and the equal-potential contours at the same time for different gate voltages. Figure 3 shows the simulation results of the 3D electron trajectories of the planar-gate CNT-FED device at the emitter voltage of 0 V, the anode voltages of 2000 V, and the gate voltage of 90 V, 150 V, and 210 V, respectively. The geometry and dimension of the simulated triode-type CNT-FED device have been depicted in Sec. II. The corresponding current density distributions on anode plates and the equal-potential contours on $x-z$ plane are shown in Figs. 4 and 5, respectively. As shown in Figs. 3, Fig. 4, and Fig. 5, the gate electrode attracts the electrons emitting from its neighboring (left- and right-side) CNT emitters in the x-direction. For the 90-V-gate-voltage case [Fig. 3(a), Fig. 4(a), and Fig. 5(a)], the attracting force from gate is not enough strong that the electron beams from the edges of left- and right-side emitters cannot, converge on an anode plate (in the x-direction). Therefore two lighting strips will appear in the same pixel of the screen due to the non-converged electron beams, and the resolution of the display will be not good under this bias condition. When the gate voltage is 150 V, as shown in Fig. 3(b), Fig. 4(b), and Fig. 5(b), the electron beams from the edges of left- and right-side emitters can converge on an anode plate (in the x-direction). And the resolution of the display will become better. When the gate voltage is increased to 210 V, as shown in Fig. 3(c), Fig. 4(c), and Fig. 5(c), the gate's attractive force becomes too strong that the linewidths along the x

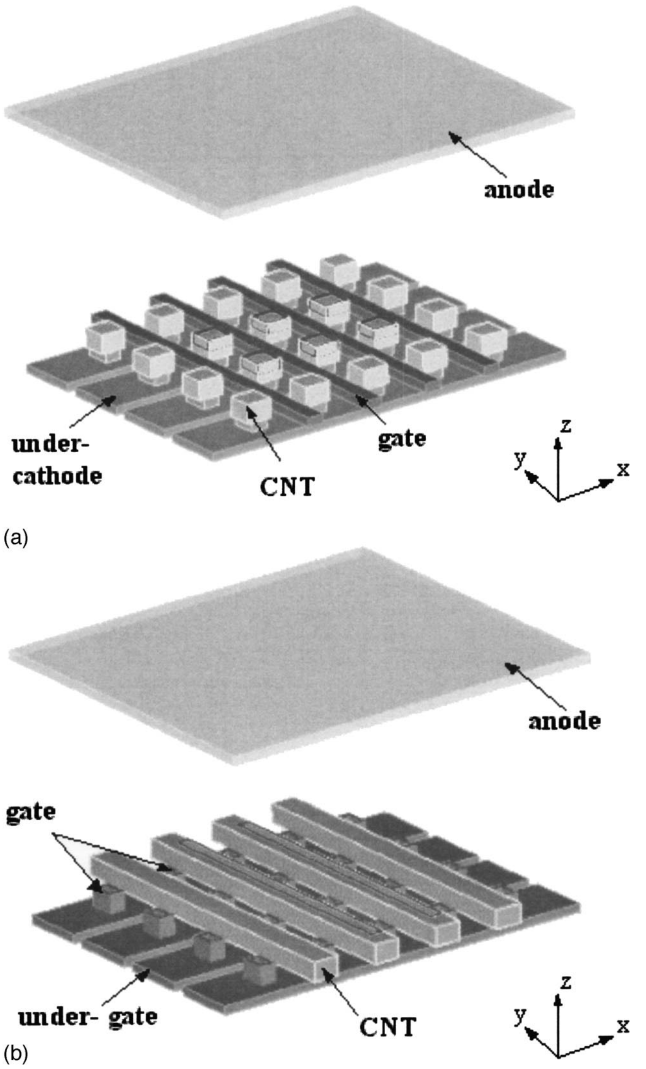

FIG. 1. Schematic of (a) planar-gate and (b) under-gate CNT-FED structures.

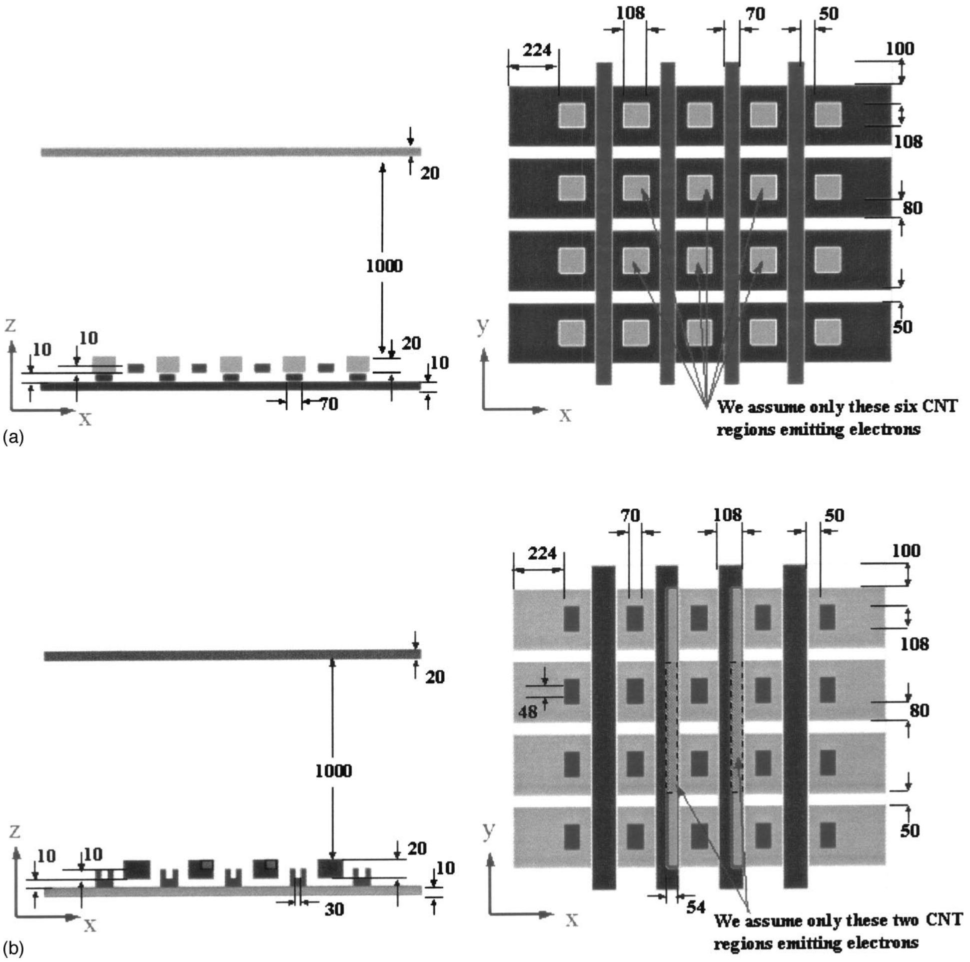

FIG. 2. Schematic of simulation domain and geometrical parameters used in the simulation, (a) planar-gate, and (b) under-gate structures. The units are in μm.

direction are larger. In this case, the display's resolution will becomes poor again. It can also be found that, from Fig. 3 and Fig. 4, due to lack of attracting fields in the y-direction, the electrons beams emitting from the edges of two neighboring emitters cannot converge in this direction. And the current density distributions look like strips instead of points on anode plates.

Figure 6 shows the simulation results of the 3D electron trajectories of the under-gate CNT-FED device at the gate voltage of 0 V, the emitter voltages of -90 V, -150 V, and -210 V, respectively, and the anode voltage of 1910 V, 1850 V, and 1790 V, respectively. And the corresponding current density distributions on anode plates and the equal-potential contours on the $x-z$ plane are shown in Fig. 7 and Fig. 8, respectively. From Fig. 6, Fig. 7, and Fig. 8, it can be found that, the gate electrode only exerts an attractive force to electrons emitting from left-side emitters. Therefore, there is no need to adjust the voltage difference between emitter and gate to converge the electrons (in the x-direction). And

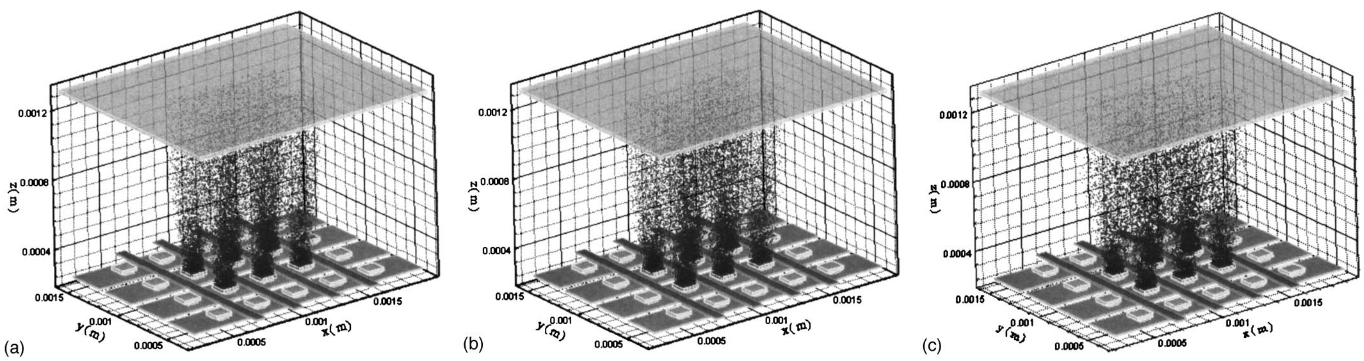

FIG. 3. Three-dimensional electron trajectories of the planar-gate structure with emitter voltage of 0 V, anode voltage of 2000 V, and gate voltage of (a) 90 V, (b) 150 V, and (c) 210 V, respectively.

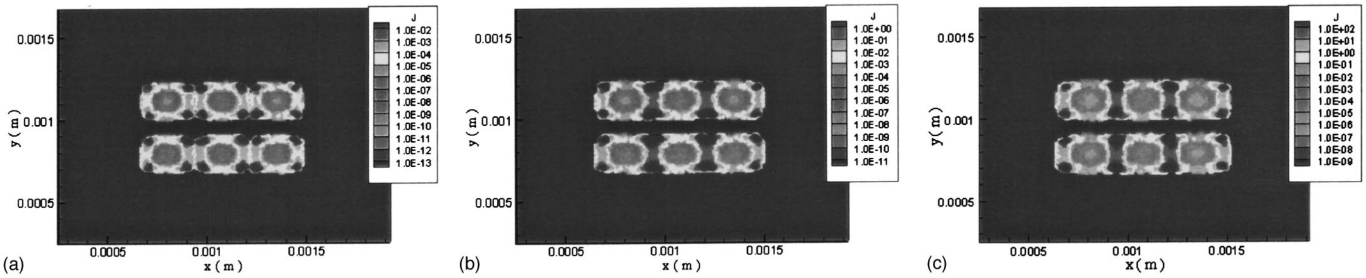

FIG. 4. Current density distributions on anode plate of the planar-gate structure with emitter voltage of 0 V, anode voltage of 2000 V, and gate voltage of (a) 90 V, (b) 150 V, and (c) 210 V, respectively.

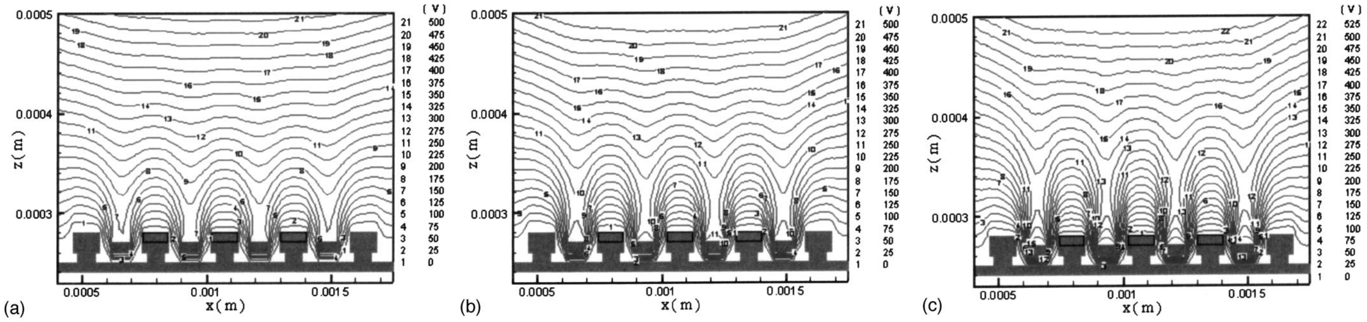

FIG. 5. Equal potential contours on the $x-z$ plane of the planar-gate structure with emitter voltage of 0 V, anode voltage of 2000 V, and gate voltage of (a) 90 V, (b) 150 V, and (c) 210 V, respectively.

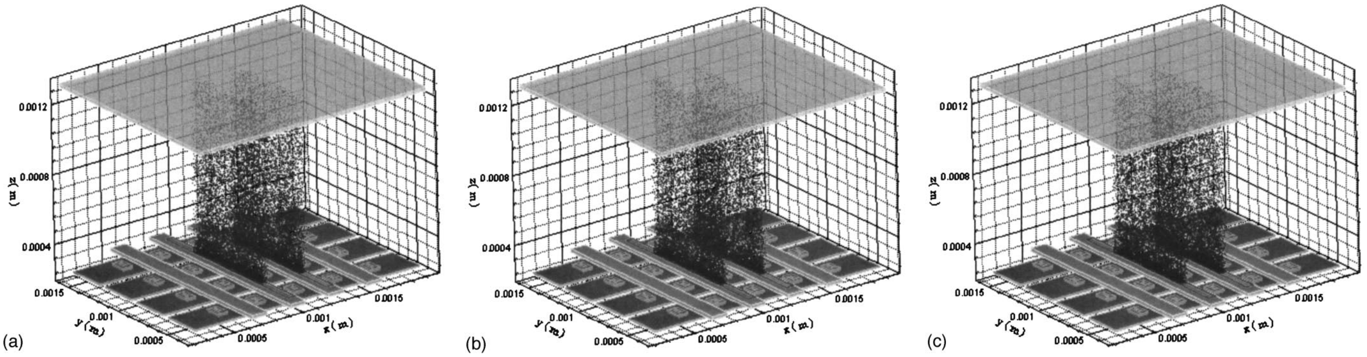

FIG. 6. Three-dimensional electron trajectories of the under-gate structure with gate voltage of 0 V and (a) emitter voltage of −90 V, anode voltage of 1910 V, (b) emitter voltage of −150 V, anode voltage of 1850 V, and (c) emitter voltage of −210 V, anode voltage of 1790 V, respectively.

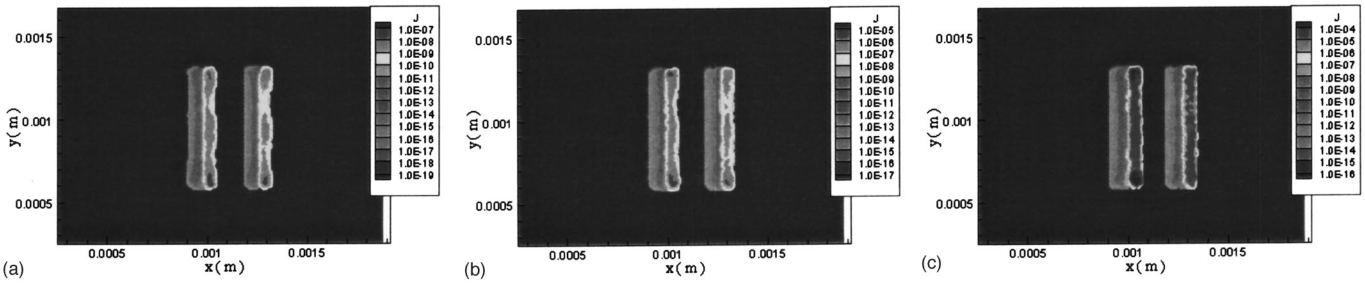

FIG. 7. Current density distributions on the anode plate of the under-gate structure with gate voltage of 0 V and (a) emitter voltage of −90 V, anode voltage of 1910 V, (b) emitter voltage of −150 V, anode voltage of 1850 V, and (c) emitter voltage of −210 V, anode voltage of 1790 V, respectively.

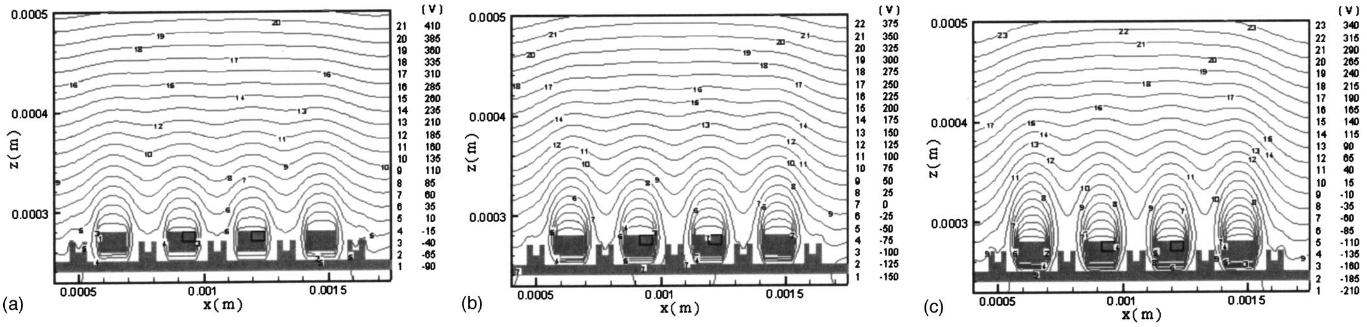

FIG. 8. Equal potential contours on the $x-z$ plane of the under-gate structure with gate voltage of 0 V and (a) emitter voltage of -90 V, anode voltage of 1910 V, (b) emitter voltage of -150 V, anode voltage of 1850 V, and (c) emitter voltage of -210 V, anode voltage of 1790 V, respectively.

in general, the resolution of the display is not bad (in the x-direction) provided that the negative emitter voltage is not too large to pull the electrons striking on other pixels. But similar to the planar-gate case, due to lack of attracting fields in the y-direction, the current density distributions look like long strips on anode plates.

Figure 9 shows the current density distributions along the x-direction at $y=0.0011$ m and on anode plate for planar-gate [Fig. 9(a)] and under-gate [Fig. 9(b)] structure devices.

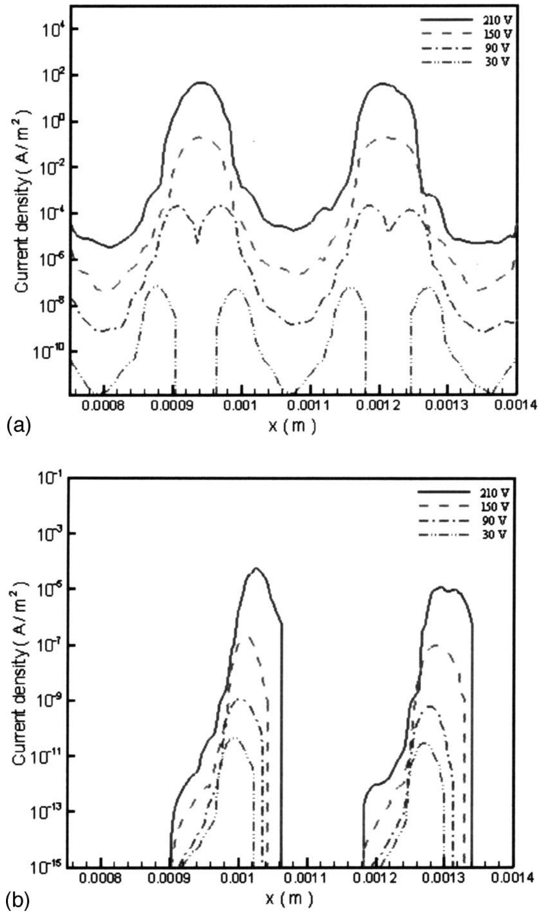

FIG. 9. Current density distributions along the x-direction at $y=0.0011$ m and on the anode plate for (a) planar-gate and (b) under-gate structures with different emitter-to-gate voltage.

It can be found clearly that, for the planar-gate structure, the current density profiles converge to single peaks gradually when the gate voltage is increased from 30 V to 150 V. But when the gate voltage is increased more (from 150 V to 210 V), the single current density profile becomes wider. For the under-gate structure, the current density profiles along the x-direction become wider monotonically as the negative emitter voltage is increased. One can also find, from the comparison between Fig. 9(a) and Fig. 9(b), that the planar-gate structure has a higher light efficiency than the under-gate structure under the same display's resolution.

IV. CONCLUSIONS

Our simulation results exhibit that for the planar-gate structure, the gate voltage has a stronger effect on the display's resolution. The good resolution is achieved only when the gate voltage is adjusted to converge the electron beams on an anode plate. For the under-gate structure, the display has a good resolution provided that the gate voltage is not too large to pull the electrons striking on other pixels. In general, the under-gate structure has a wider gate-biased operating condition, but the planar triode structure has a higher light efficiency under the same resolution. Due to the lack of field effect in the y-direction, the spot size of the current density on the anode plate looks like strips instead of points. So the resolution of the display will be affected by this factor.

ACKNOWLEDGMENTS

The authors would like to acknowledge the National Center for High-Performance Computing for providing the MAGIC code and computer facilities.

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