SIMULATION OF THIN-FILM FIELD EMITTER TRIODE

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Abstract
We carried out 2-dimensional numerical calculations of electrostatic potential for triode field emitters with planar cathodes using the finite element method. As it turned out, the conventional triode structure with a planar cathode suffered from large gate current and wide spreading of emitted electrons. To circumvent these shortcomings, we proposed a new triode structure. By simply inserting a conducting layer of proper thickness on top of the cathode layer, we were able to modify the electric field distribution on the cathode surface so that low gate current and electron-focusing effect were achieved, simultaneously.

1. Introduction

Search for the novel carbon films, which possess good enough emission properties to be used as the cathode material for next generation field emission display, has been vigorously conducted for the last few years. The fabrication of triode-type field emitters based on new carbon materials has also attracted a lot of attention [1]. In general, carbon-based thin films emit electrons at very low electric field and, therefore, do not require sharp tip formation for the triode fabrication. However, the electric field distributions which flat carbon-film cathodes experience are quite different from those of sharp-tip cathodes because of the geometrical difference. Nevertheless, the details of the electron emission from the triode-type emitters with flat cathodes have not been studied systematically [2-4].

Recently, we successfully fabricated triode field emitters with a conventional gate structure and planar cathodes of carbon nanoparticles (CNPs), which showed relatively smooth surface morphology [5,6]. The field-emission measurement and the 2-dimensional numerical simulation of these CNP triode emitters showed that large gate current and wide spreading of emitted electrons were inherent characteristics of triode field emitters with planar cathodes.

In this work, we numerically calculated the electrostatic potential distributions, using the finite element method, on the surfaces of planar cathodes of triode-type field emitters, and investigated the corresponding uneven local electron emission and the spatial variation in electron trajectory. Moreover, we proposed a modification in the structure of planar-cathode triodes, which can circumvent the aforementioned shortcomings of triode emitters with planar cathodes.

2. Numerical Simulation

We carried out 2-dimensional numerical calculation of electrostatic potential using the finite-element-method code ANSYS^{TM} to determine the electric field distribution for various triode structures. The ANSYS program uses the Laplace's equation as the basis for static electric field analysis without taking the space-charge effect into account [10]. Since the typical current densities of triode emitters with carbon cathodes were not high enough to induce the space-charge effect [8], the use of ANSYS program was justified. Electron emission from cathode surface and trajectories of field-emitted electrons were calculated using the Fowler-Nordheim's field-emission equation [9] and the equation of motion, respectively. All the simulation parameters were taken from the experimental result of a triode emitter with carbon-nanoparticle cathode, which we fabricated [5].

3. Results and discussion

Figure 1 shows the schematic structures of triode field emitters with planar cathodes, for which the simulations were carried out. The triode emitters with the conventional structure, shown in Fig. 1(a), were previously fabricated by incorporating diamond, diamond-like carbon, and amorphous carbon films as cathodes [2,3,7]. Recently, we also succeeded in fabricating a triode emitter with the conventional structure using a CNP-film cathode. Note that the electric field has an azimuthal symmetry for both of these triode-emitter structures shown in Fig. 1, and its strength on the surface of the flat cathode layer depends on the radial distance, *r*, from the center and the gate voltage V_g for the given gate-oxide thickness $h: E = E(r, V_g : h)$.

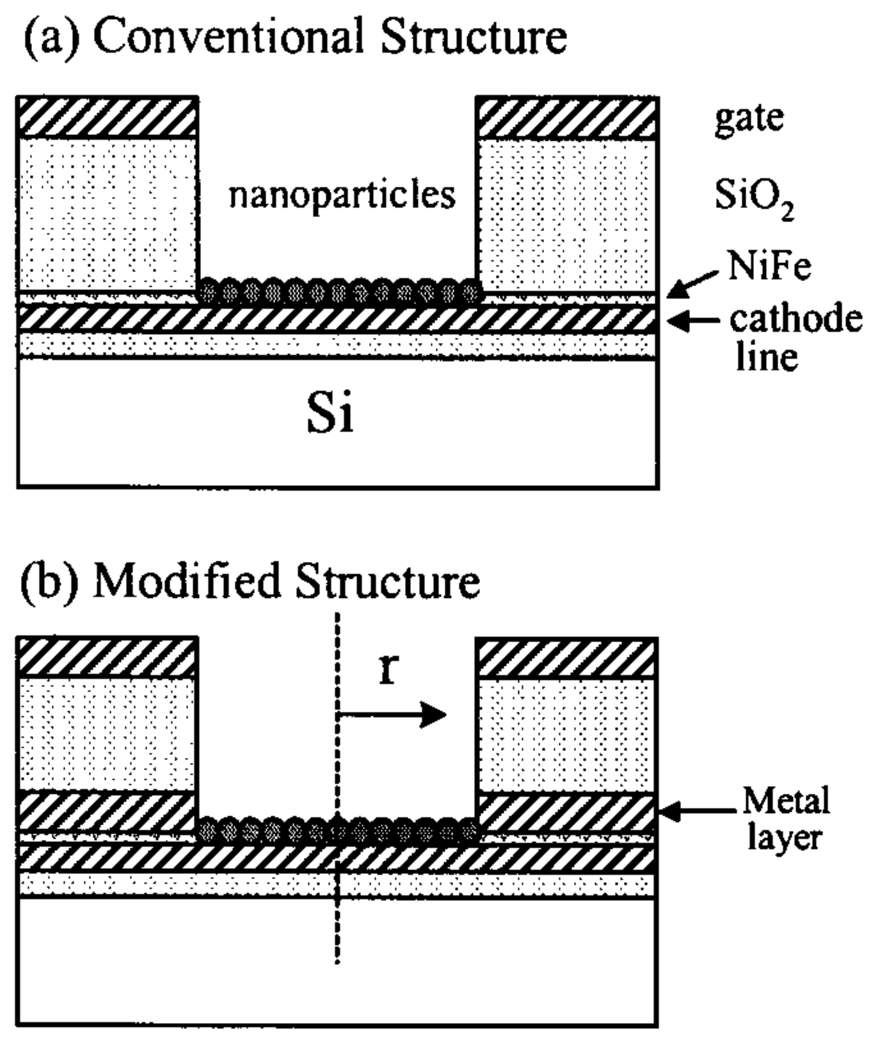

FIG.1 The schematic structures of triode field emitters with planar cathodes: (a) conventional structure, (b) modified structure.

The typical electric field distribution on the surface of the planar cathode of the conventional-structure triode emitter is presented in Fig. 2(a). The geometrical parameters with which we carried out the numerical calculations were the gate-oxide thickness $h = 1.5\,\mu m$, the gate thickness $d_g = 0.2\,\mu m$, the gate-anode distance $d_{ga} = 60\,\mu m$, and the gate-hole radius $r = 6\,\mu m$, respectively, and the anode-bias voltage was set at $V_a = 500V$. Note that the electric field is larger near the cathode edge than at central area; the variation of ~16 and ~21 V/μm was observed over the radial distance of 6μm at V_g of 45 and 60 V, respectively. It is worth emphasizing that this radial variation would appear enhanced by the field enhancement factor β in the local electric field $F = \beta E$. Consequently, the emission sites located near the edge of the planar cathode contribute most of the emission currents due to the $\exp(-1/F)$-dependence of the Fowler-Nordheim emission current. The inset of Fig. 2 shows the radial-position-dependent variation of the emission current from the identical emission site of work function $\phi = 5.0\,eV$, $\beta = 120$, and emission area $S = 7.9 \times 10^3\,nm^2$ at $V_g = 60V$; these Fowler-Norheim parameters were determined from the field-emission result of our CNP triode emitter, which we already reported elsewhere [5], and used throughout this work in simulating the emission current.

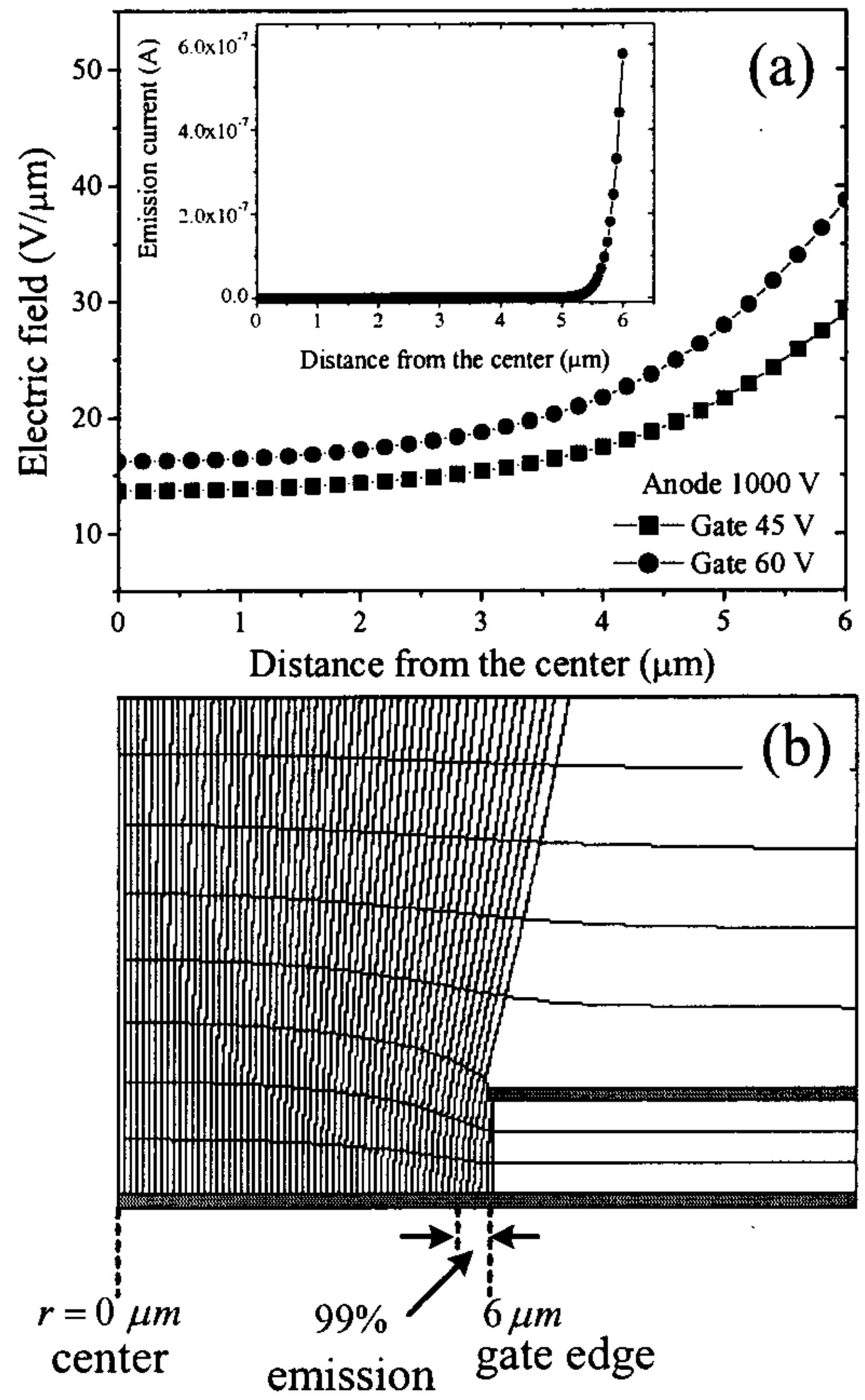

FIG. 2. Radial position dependence of the electric field on the planar cathode surface in a triode emitter with the convention structure (a), and typical emitted electron trajectories for the gate voltage of 30 V at the anode voltage of 500V (b); the small area near the gate edge is responsible for the 99% of emission current. The variation of the emission current from the identical emission site located at different radial positions is shown in the inset.

Figure 2(b) shows the typical electron trajectories and the equipotential lines of the conventional-structure triode emitter at the gate voltage of 30 V; note that the small area near the gate edge is responsible for the 99 % of total emission current. It is quite obvious that the large gate current and the wide spreading of emitted electrons are the inherent characteristics of conventional-structure triode field emitters with planar cathodes. As a way to circumvent these problems, a few different approaches have been suggested; the fabrication of a smaller concentric cathode within a gate hole by strictly restricted deposition of electron-emitting material and the fabrication of a pedestal-shaped cathode were the typical examples [2,3]. However, these approaches make the triode-fabrication process a lot more complicated, and moreover, the problem of wide spreading of emitted electrons is not alleviated, which necessitate an extra electrode to focus emitted electrons.

One alternative to minimize the gate current and electron spreading is to increase the anode voltage so that the electric field at the central part of cathode becomes larger than their counterpart at the edges. At appropriate anode-bias voltages, only the central part of the cathode can attain the electric-field strength necessary for sufficient electron emission, and therefore only very small gate current is expected [4]. However, the operation of conventional-structure triode emitters in an anode-bias-assisted mode has a few drawbacks. First, we cannot vary the anode voltage and the anode-gate separation independently. Second, excessively large anode voltage is required to achieve the aforementioned anode-bias-assisted effects. Note that the high anode-bias voltage, moreover, can cause serious problems such as arcing between the gate and anode electrodes.

To circumvent the shortcomings of the conventional-structure triode emitters with planar cathodes, we devised a modified triode structure presented in Fig. 1(b); an extra metal layer of proper thickness was inserted on top of the cathode layer to alter the electric-field distribution on the cathode surface. Figure 3(a) shows the gate-voltage-dependent spatial variation of the electric field on the planar-cathode surface in the triode emitter with the modified structure. It is clear that the electric field in the central area becomes larger than that near the gate edge. Moreover, the uniform electric-field distribution over the large area of the planar cathode appears, together with the sharp drop of electric field near the gate edge. Consequently, most of the emission currents originate from the central area of the cathode as shown in Fig. 3(b), which along with the electron-focusing effect guarantees the low gate current; Fig. 3(b) shows the emission-current distribution at the gate-bias voltage of 40 V for the anode voltage of 500V. The focusing of the emitted electrons in the modified triode structure is well represented in the typical emitted-electron trajectories presented in fig. 3(c).

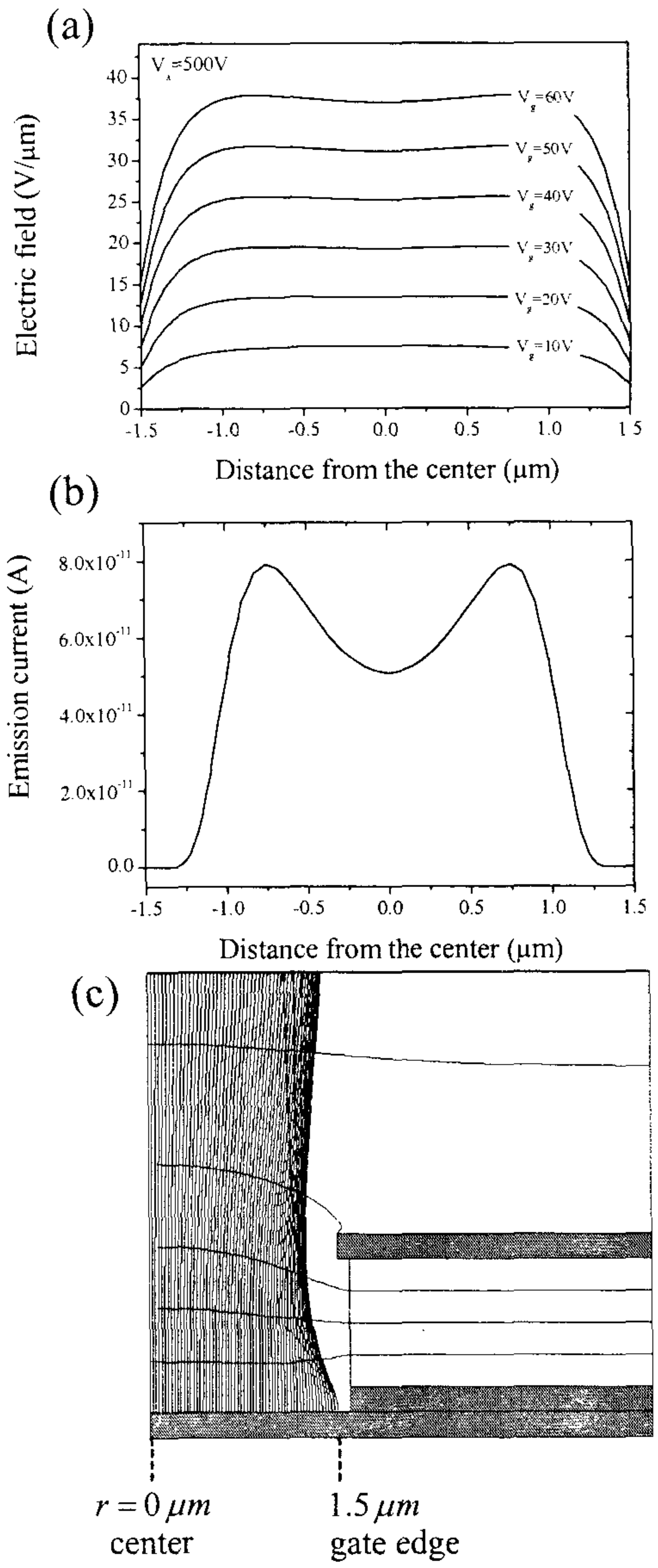

FIG.3 Radial position dependence of electric field at different gate-bias voltages (a), the spatial distribution of the emission current at the gate-bias voltage of 40 V for the anode voltage of 500V (b), and the electron trajectories (c) of triode emitters with the modified structure.

In Fig. 4, we compared the electric-field distributions of the conventional-structure and the modified-structure triode emitters with the identical geometrical parameters. Note that the electric field at the central region of the modified structure is a little bit lower than that of the conventional structure. However, less than 10% increase of the gate voltage is sufficient to restore the central-region electric field of the modified structure to the level of the conventional structure. It is worth emphasizing that this simple scheme for the electric-field modification of triode emitters with planar cathode, insertion of a proper-thickness conducting layer on top of the cathode layer, is flexible enough so that it can be used for the fabrication of triode emitters of any size and shape, and, moreover, can be incorporated into relatively inexpensive triode-fabrication methods such as the screen-printing.

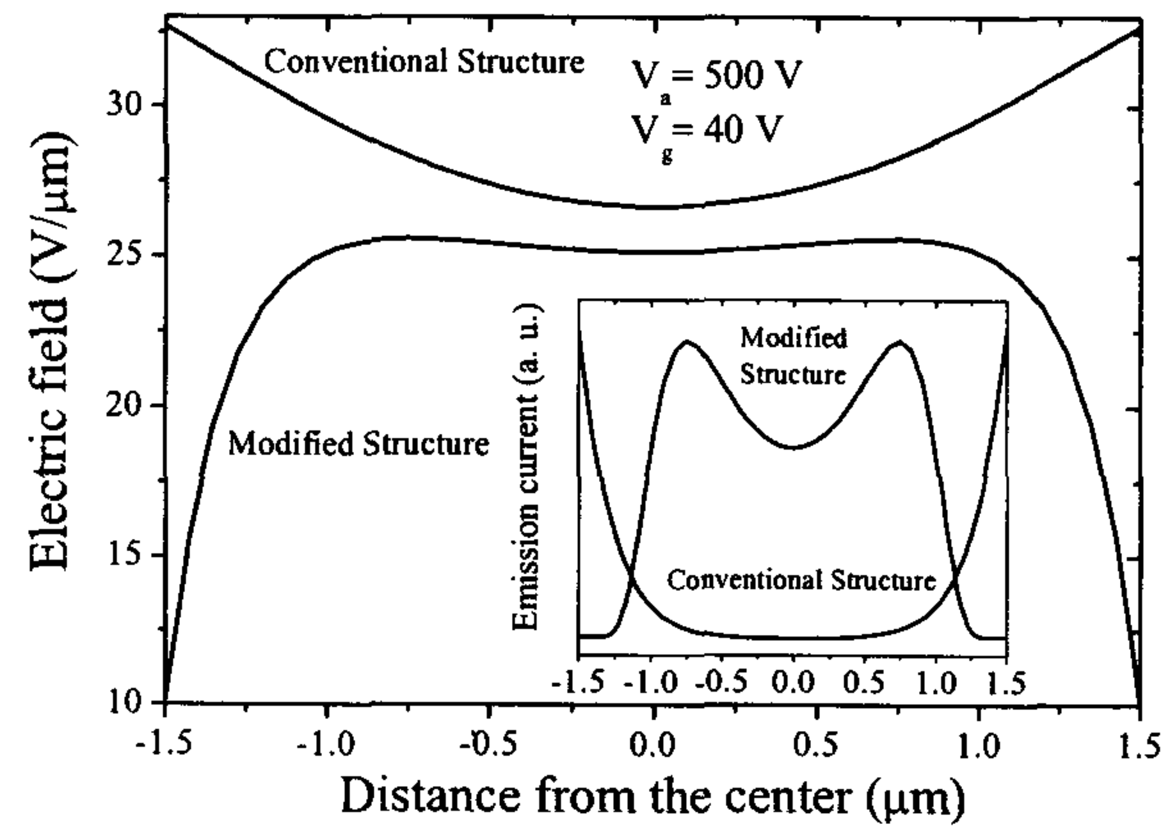

FIG.4 Comparison between the electric-field distribution of the conventional triode structure with that of the modified triode-emitter structure; geometrical parameters are identical. The radial position dependence of emission currents is compared in the inset.

4. Conclusion

We proposed a simple modification of triode structure to overcome the shortcomings of conventional-structure triode emitters with planar cathodes, which are the large gate current and the wide spreading of emitted electrons. Carrying out the finite-element-method calculation, we showed that the field distribution on the cathode surface could be easily modified through the simple insertion of an extra conducting layer on top of the cathode so that the significant portion of the emission current originate from the central region of the planar cathode. Together with the improvement in electron focusing, the preferential electron emission from the central region of the cathode resulted in the substantial reduction of the gate current.

5. References

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