Field emission device modeling for application to flat panel displays

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A computer model has been developed for determining the electrical characteristics of field emission devices. Numerical techniques are employed to determine the electric field distribution and electron trajectories in the modeled device. Using the electron trajectories and emission current density determined from the Fowler–Nordheim equation, electrode currents are found. The current–voltage characteristics are constructed using superposition of electric field solutions. Simulation results are presented for a single vertical triode of a field emission flat panel display. The cathode tip has a radius of curvature of 20 nm and is centered in a 2 μm diam gate aperture. The anode is typically biased at 400 V and spaced 0.2 mm from the cathode. Simulation results indicate turn-on at 75 V and 0.1 μA emitted at a gate drive of 95 V. Gate current is negligible. Peak-to-peak gate drive for a 1000 line field emission display having 100:1 contrast ratio is found to be less than 50 V for such a structure.

I. INTRODUCTION

In the past, field-emission sources of electrons have not been practical for many applications due, in part, to the relatively high voltages required. With the development of vacuum microelectronic field-emission devices which can operate at relatively low voltages,[1,2] several new applications are now being considered. Field-emission flat panel displays are of interest because of their potential for ultrahigh resolution, thin size, low power consumption, and good color image quality.[3] Such properties are particularly desirable for portable computer and electronic avionics displays, for example. Though several flat display technologies have been developed for such applications, none of them can yet deliver the visual performance of the typical shadow-mask color cathode ray tube (CRT). Active matrix liquid crystal displays are perhaps closest to the CRT in visual performance, but they are inherently inferior in several regards and are significantly more expensive. Field-emission flat panel displays rely on the same optical transduction mechanism as CRTs, cathodoluminescence, and may be able to deliver similar price and performance if development hurdles can be overcome. A long range goal of this work is to help surmount some of these hurdles, which include further reduction in drive voltages, determination of optimal drive schemes, enhancement of emission stability, and identification of suitable phosphors.

As with any electronic device, good models of electrical behavior are necessary for design and simulation. The Ebers–Moll and hybrid-π models are examples for the case of bipolar junction transistors. Since many applications require that individual devices be incorporated into larger systems, system models become as useful as the device models from which they are derived. An equation for the frequency response of a transistor amplifier is an example. Models are often embodied in simulation software, as in the case of circuit simulators for integrated circuit (IC) design. Such powerful and general models, as these, do not yet exist for microelectronic field-emission devices, but are needed for both device and system development. In this article, we present work leading to the development of a set of field-emission device models which can be used for design of a large-scale flat panel display. The present work involves computer simulation of the electrical behavior of a vertical triode.

In principle, Poisson's equation can be solved for the distribution of electric potential in a device of arbitrary electrode geometries and voltages, and the electric field can be determined by differentiation of the potential. If current density in the device is low, space charge effects can be reasonably neglected and Poisson's equation simplifies to Laplace's equation. This is the case for most display applications, where peak currents of ∼0.1 μA/emission tip have been shown to be adequate.[4] Exact analytic solutions to Laplace's equation have been determined for electrode geometries approximating those of practical microelectronic field emitters. Cade,[5] for example, found solutions to the electric field from the charge distributions within the electrodes. Expressions for these charge distributions were chosen so that the electrode boundaries could be approximated by equipotential contours. This type of approach gives significant insight into generic device characteristics, but does not allow determination of the effects of subtle changes in electrode geometry such as changing the thickness of a planar gate.

Numerical solutions to Laplace's equation can be found for precisely defined geometrical models of field-emission devices. Orvis and co-workers[6] used a two-dimensional (2D) finite difference simulation to find the electric field in a triode structure. They determined the emission characteristics from the field strength at the very top of the tip using the Fowler–Nordheim equation with a field enhancement factor to fit experimental data. Numerical simulation of electron trajectories verified that all emission current was collected at the anode for the particular device structure simulated, so the device electrical characteristics could be determined directly from the emission characteristics. This approach is not applicable to cases of significant gate current. Feeney and co-workers[7] went a step further by determining the emission current density at many points on the cathode tip and integrating to obtain the total emis-

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sion current. We take this general approach further by also calculating the gate and anode currents from the electron trajectories.

II. PROCEDURE

Conical cathodes with circular gate apertures have been implemented in both metal and silicon for application to displays.[4,8,9] Cathode-tip radius is normally in the range of 1–100 nm. Cathode height and gate aperture diameter are normally a micron or two. The anode may be tens of microns to several millimeters away from the cathode-gate substrate. Though pyramid-shaped cathodes and square-gate apertures are also of interest, the aforementioned structure is particularly simple to analyze due to cylindrical symmetry. We use a finite-element numerical simulation to solve Laplace's equation in two dimensions for the electric potential.[10] The finite element technique is well-suited for modeling devices having fine structural detail and complex electrode shape. This is because the location of finite element nodes is unconstrained and the mesh size is variable. Numerical differentiation gives the electric field at the nodes of the finite element mesh. Two electric field solutions are determined, one by setting the gate to 1 V with the anode at zero and the other by setting the anode to 1 V with the gate at zero. Since the Laplacian operator is linear, the field solution for any set of gate and anode voltages can be determined from the linear combination of these two basis solutions. The cathode is always at 0 V for reference.

Electron trajectories are determined from a finite difference solution to the equations of motion of charged particles in an electric field. In the case of cylindrical symmetry, the equations of motion simplify to the familiar 2D Cartesian form,

$$\frac{d^2r}{dt^2} = -(q/m)E_r, \tag{1}$$

$$\frac{d^2z}{dt^2} = -(q/m)E_z, \tag{2}$$

where r and z are the spatial coordinates defined in Fig. 1, t is time, q and m are the electron charge and mass, respectively, and E_r and E_z are the r and z components of the electric field. The electric field is unaffected by emitted electrons in the case of low current density. Equations (1) and (2) are numerically integrated using the fourth-order Runge–Kutta–Fehlberg method. A fifth-order procedure estimates the local truncation error, which is used to adaptively control the step size of the fourth-order integration. Since the finite element solution determines the electric field only at the nodes of the mesh, quadratic interpolation is used to find the field at other points of interest. Trajectories are initiated at closely spaced points on the cathode surface which coincide with nodes of the finite element mesh. When an electron approaches within 1 nm of an electrode, its trajectory is terminated.

The emission density of electrons from a cold cathode has been expressed in terms of the electric field at the cathode surface by the Fowler–Nordheim equation,

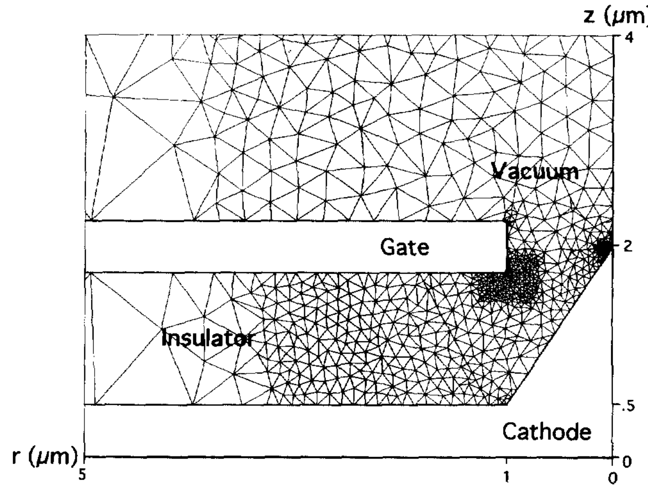

FIG. 1. 2D model of a vertical field-emission triode. The cathode is 1.25 μm high with a tip radius of 20 nm. The gate aperture is 2 μm in diameter. The triangular finite element mesh used to determine the electric field is made very fine in critical regions such as near the cathode tip. The anode is 0.2 mm from the gate and does not show in the figure.

$$J = aE^2 \exp(-b/E), \tag{3}$$

where J is the current density, E is the electric field strength, and a and b are emission parameters. The emission parameters are $a = 3.67\times10^{-7}$ A m^2/V^2 and $b = 5.91\times10^{10}$ V/m based on low-level emission and the silicon work function of 4.2 eV. Emission current is actually much higher than predicted by Eq. (3) due to surface microroughness and variations in work function. The electric field is normally multiplied by an enhancement factor to account for this. Explicitly,

$$J = ac^2E^2 \exp(-b/cE), \tag{4}$$

where c is the enhancement factor. The enhancement factor is sometimes taken to include enhancement of the electric field due to the presence of the cathode tip itself, but we account for this by determining the local electric field directly. An emission enhancement factor of $c = 3.3$ was determined by modeling the triodes fabricated by another group and fitting the simulated gate drive characteristic to their published data.[9] Those triodes are similar to the axially symmetric silicon devices being developed within our experimental program.[11]

The current density at each node on the cathode surface is determined from the electric field solution at that point by using Eq. (4). The emission current corresponding to each node is given by this current density times the area corresponding to the node, where the area is found from the surfaces of revolution of line segments between nodes. Total cathode current is found by summing the current of all nodes on the cathode surface. Electron trajectories are initiated at nodes progressively further from the top of the cathode tip until the emission current for a single node drops below 0.01% of the current at the node at the top of the tip. The gate and anode currents are determined by summing the currents of all trajectories that terminate on these electrodes. I–V characteristics are generated by determining the electric field for each set of electrode voltages, calculating the electron trajectories, and determining the resultant electrode currents.

III. RESULTS

Figure 1 shows the geometry and finite element mesh used to model triodes with sharp silicon tips. The cathode is 1.5 μm high and has a radius of curvature of 20 nm at the tip, corresponding to oxidized-sharpened silicon tips.[9] The gate is 0.5 μm thick and vertically centered on the tip of the cathode. The corners of the gate are rounded with 50 nm radii. The insulator is 1.25 μm thick with a relative dielectric constant of 3.9 to model silicon dioxide. The anode is 197.5 μm from the cathode tip and does not show in the figure. The entire simulation area is 200 μm in the z direction by 250 μm in the r direction. The mesh has under 4000 finite element triangles and is made very fine near the cathode and other critical regions.

Simulated electron trajectories are shown in Fig. 2. Figure 3 is a plot of the current density distribution at the anode for typical operating conditions. The behavior of the distribution near $r=0$ is not physically accurate due to error in the electric field solution near the axis of symmetry. This is explained further in Sec. IV. The simulated gate drive characteristic is shown in Fig. 4.

IV. DISCUSSION

The 2D model used for triode simulation is the same for conical emitters with circular gate apertures as it is for wedge emitters with rectangular gate apertures. The coordinate system determines which structure is actually being modeled. The cylindrical form of Laplace's equation in two dimensions is suited to conical emitters,

$$\frac{\partial^2 V}{\partial r^2}+\frac{1}{r}\frac{\partial V}{\partial r}+\frac{\partial^2 V}{\partial z^2}=0, \tag{5}$$

while the Cartesian form in 2D is suited to long wedge emitters,

$$\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial z^2}=0. \tag{6}$$

Three-dimensional analysis may be required to accurately model anisotropically etched emitters and gate apertures defined with square masks. All of our analysis was done in cylindrical coordinates and assumed cylindrical symmetry. Our initial modeling also assumed perfectly conducting electrodes.

We have followed the common practice of using a field-enhancement factor in the Fowler–Nordheim equation. This approach does not have a theoretical basis, but in practice it provides a parameter for fitting empirical data. We feel that the technique is justified for use as a tool to aid in developing device models for system simulation, but intend to modify it to accommodate modeling of extremely sharp tips in the future.

Close examination of the electron trajectories reveals that the electrons emitted from the very top of the cathode tip pull away from the axis of symmetry on their way to the anode [Fig. 2(a), for example]. This contradicts the requirements of symmetry and affects the current density distribution at the anode (Fig. 3) near $r=0$. This unphysical electron behavior near the z axis is due to weak enforcement of axial symmetry in the electric field solution and a remedy is currently being sought.

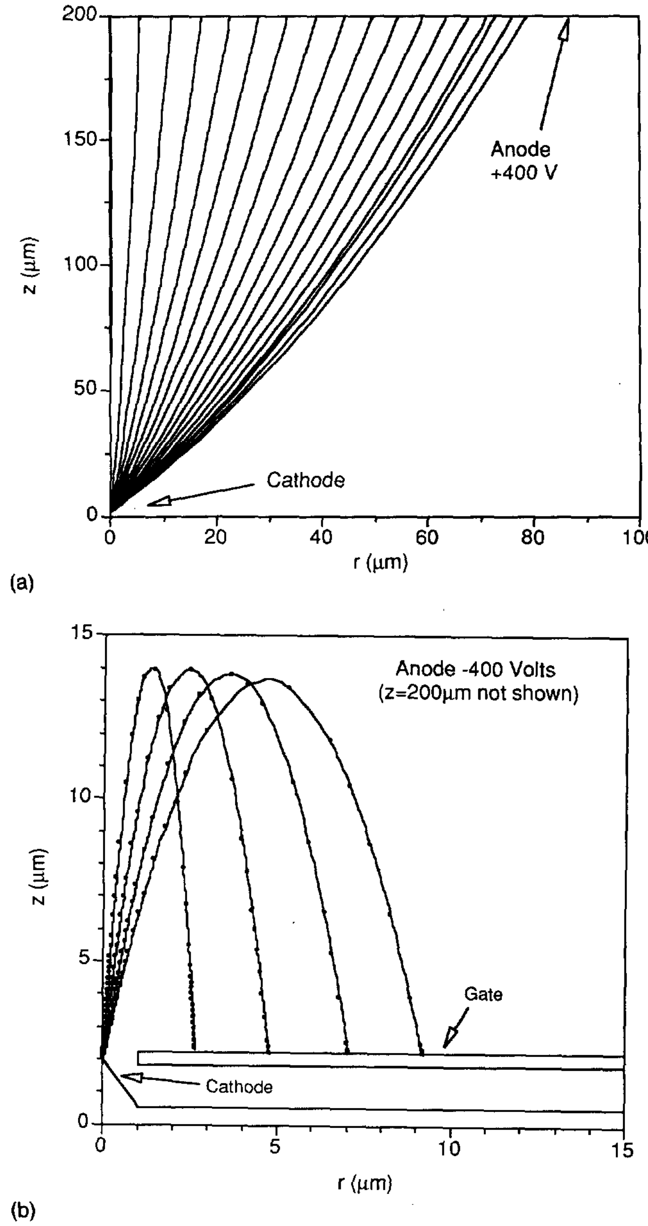

FIG. 2. Simulated electron trajectories. In (a) the gate voltage is +100 V and the anode is +400 V with respect to the cathode. The plotted trajectories represent more than 99.99% of the cathode current. Note that the r and z axes have differing scales. The irregular spacing spacing between some trajectories is due to the corresponding spacing between cathode nodes. In (b) a sample of trajectories is shown for an anode voltage of −400 V.

We believe that the tail of the distribution of Fig. 3 is not significantly affected by the simulation artifact near $r=0$; therefore, this method is useful for optimizing display pixel spacing. The data indicate that essentially all the emission current (99.99%) is collected within a 75 μm radius at the anode. Assuming a 25 emitter array on 5 μm

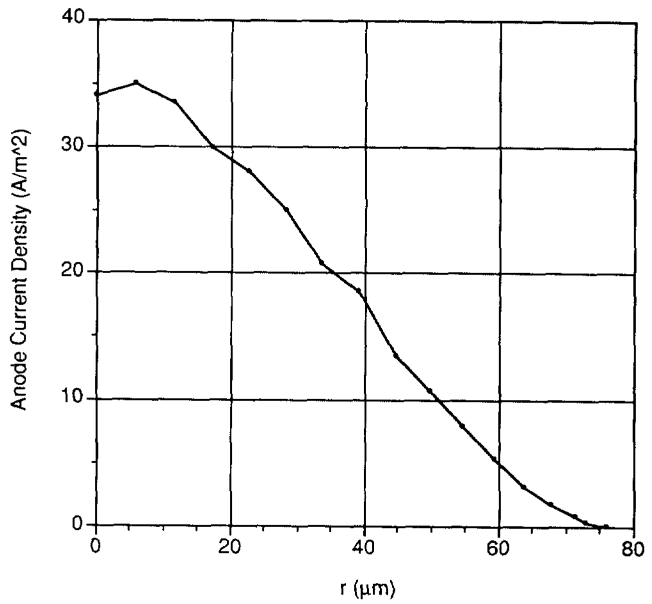

FIG. 3. Current density distribution at the anode as a function of radial position for the gate biased at 100 V and the anode at 400 V. The results for $r<20$ μm have a large uncertainty due to weak enforcement of axial symmetry in the electric field simulation.

centers, this allows a maximum display resolution of ~2 lines/mm (50 dots/in.) for a spatially multiplexed color display. This is adequate for color television, but suggests that some modification must be made to meet the requirements of computer and avionics displays. These results depend on the anode-to-grid voltage and distance, which were chosen based on the prototype display reported by Meyer.[4]

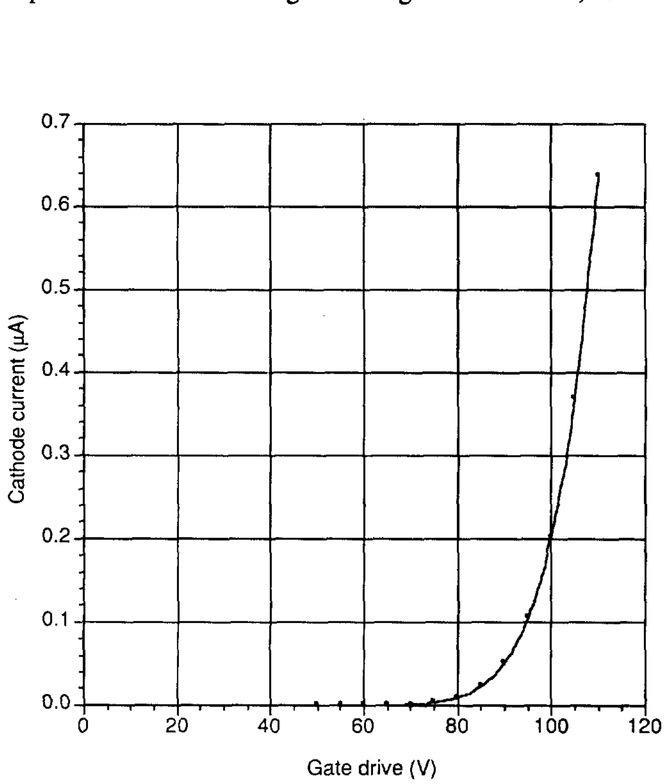

FIG. 4. Simulated drive characteristic of a silicon field-emission triode. Due to the large anode-cathode spacing, the drive characteristic is independent of anode voltage over a wide range.

Gate currents of ~0.1% of the anode current have been reported for cylindrically symmetrical vertical triodes[12] Our simulation showed vanishingly small gate current for positive anode potentials. The nonzero gate current of real devices might be explained by local field emission from fine structure on the sides of the cathode cone. Total emission current should be insensitive to anode voltage in a device where the anode is far from the other electrodes, and this was confirmed in the simulation. Cathode current for the device of Fig. 1 was constant for anode voltages between −500 and +500 V. Silicon triodes with distant anodes have been reported with turn-on voltages from ~10–100 V.[1,9] This simulation predicts a turn on voltage of 75 V, near the value reported for prototype field emission displays.[4] The gate drive required for a field emission display can be determined by determining the maximum and minimum currents required to meet brightness and contrast goals. Assuming a peak cathode current of 0.1 μA/tip for acceptable brightness of a 1000 line display with 100:1 contrast ratio, the off-state current must be less than 1 pA. The simulated drive characteristic of Fig. 4 indicates that less than 50 V peak-to-peak is sufficient to meet this condition. Simulation of sharper cathode tips indicated reduced drive requirements. Smaller gate apertures are also expected to help reduce the drive requirement.

V. SUMMARY

Computer modeling capability for field emission devices has been developed to aid in the understanding and development of field emission triodes and displays. The model allows determination of electron trajectories and current-voltage characteristics. A vertical triode with a sharp silicon cathode and a distant anode has been used for initial modeling of a field-emission flat panel display. The results indicate a turn-on voltage consistent with that reported for prototype field-emission displays. The simulation can also be used to investigate other interesting device concepts such as recessed gates and focus electrodes. We intend to use the model to aid in the design of silicon triode structures and to refine the simulation model as experimental data is generated.

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