BEAM FOCUSING FOR FIELD EMISSION FLAT PANEL DISPLAYS*

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A combination of finite element and finite difference techniques have been used to simulate the performance of microfabricated gated field emitters for flat panel display applications. The computer model has been verified against both analytic models and experimental data for unfocused devices and then applied to the study of focused structures for which sufficient models and data are not yet available. Prior reports of aperture focusing are confirmed and expanded to include gate drive characteristics and beam widths. A concentric electrode design is also considered and found to be potentially applicable to flat panel displays.

INTRODUCTION

The proximity-focused approach was used in an early color field emission display (FED) prototype [1]. The switched-anode approach was later used to demonstrate a fully functional color FED [2]. The maximum anode voltage of both of these approaches is much lower than that used in conventional cathode ray tubes (CRT's) and requires the use of low-voltage phosphors. Focusing the electron beams could allow proven CRT phosphors to be used by permitting larger anode-cathode spacing and voltage without a loss in resolution or color purity. The aperture-focused approach has long been considered a possibility and previous computer experiments confirm its effectiveness [3,4]. Other focusing designs have also been proposed [5,6] but are not tailored to flat panel display applications.

METHOD

A commercial finite element software package [7] is used to solve for the electric field in the modeled devices. Custom code was developed for determining electron trajectories and device currents [8]. Emission current density is calculated from the Fowler-Nordheim equation at points along the cathode surface. Trajectories are calculated using a fourth-order finite difference integration of the electron equations of motion. Far from the cathode (typically 100 μm), the trajectories are extrapolated using the exact solution for electrons in a uniform electric field. This is reasonable in cases where the anode substrate is an isopotential surface. Electrode currents and beam width are found from the trajectories.

RESULTS

Verification

Modeled trajectories were confirmed against the exact solution between infinite parallel plates. They satisfy conservation of energy for arbitrary structures. The final verification step involved comparison to experimental gate drive characteristics and spot sizes provided by LETI for proximity focused emitters. Results are compared in figure 1 and confirm adequate accuracy of the model for our intended application.

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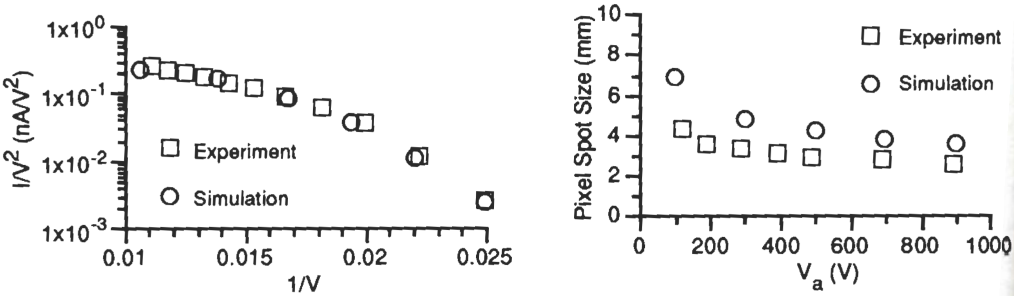

Figure 1. Comparison of simulated and experimental results: a) Fowler-Nordheim plot of gate drive characteristics, and b) spot size of a 10,000-tip pixel. The F-N data does not show the characteristic straight-line behavior because of cathode series resistance.

Proximity Focus

A representative geometry was used to model the gated cathode of a proximity-focused device. The conical cathode has a spherical tip with 20 nm radius centered in a one micron diameter aperture. The calculated current-voltage characteristic is plotted in figure 2. The anode exerts a minimal influence over emission in most display applications because it is far from the cathode tip. Gate current is found to be zero, but real devices demonstrate a small amount of gate current due to emission from surface irregularities on the sides of the cathode. This gate current is normally not significant since the capacitive gate current is far greater in matrix-addressed displays. A prototypical display with 1000 lines, several hundred cd/m^2 of luminance and 100:1 contrast is found to require 35 $V_{p\text{-}p}$ of gate drive. Calculated spot size is plotted as a function of anode-to-cathode spacing in figure 3. High resolution proximity-focused displays require small spots and therefore small anode spacing with correspondingly low anode voltage. Calculated trajectories are shown in figure 4.

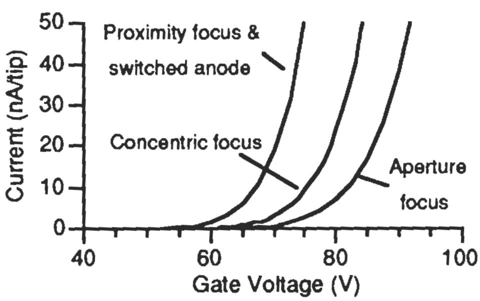

Figure 2. Calculated gate drive characteristics for the devices being considered.

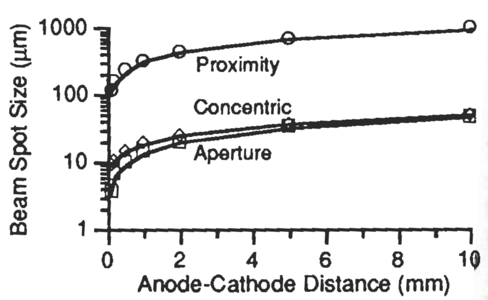

Figure 3. Beam width at the anode for a single tip. Beam current is 50 nA. Anode-gate field strength is 4 kV/mm. Focus bias is fixed.

Switched Anode

The gate drive characteristics of switched-anode and proximity-focused devices are similar since the differences in anode structure have a small affect on the electric field near the field emission tips. Net anode current may be smaller in switched-anode devices, however, since some current escapes the active region of the anode and falls back on the gate. This is demonstrated by the calculated trajectories of figure 5. This geometry is an abstraction of the switched-anode geometry and is unrealistic for use in real displays, but it clearly demonstrates the origin of gate current and the excitation of individual phosphor regions.

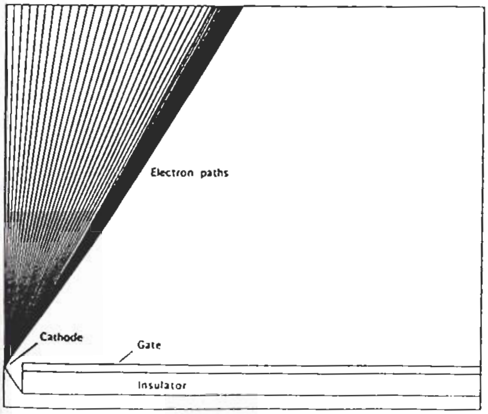

Figure 4. Proximity-focused field emission tip and calculated electron trajectories. Due to cylindrical symmetry, half of a cross sectional view is shown. The anode is far away and does not show in this close-up view.

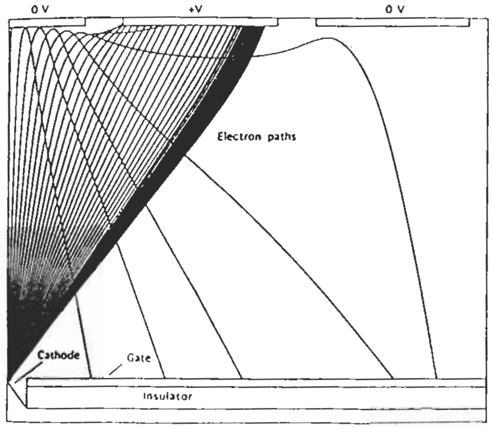

Figure 5. A simplified switched-anode device showing calculated electron trajectories when only one phosphor region is biased to anode potential. Practical structures have much larger phosphor regions.

Aperture Focus

An aperture-focused tip is shown along with electron trajectories in figure 6. The gate drive characteristic is plotted alongside the proximity-focused curve in figure 2. The drive of the prototypical display is 50 V_{p-p} when highly focused, verses 35 V_{p-p} for the proximity focused structure. The integrated circuits required to drive the rows of the display become significantly more expensive above about 40 V_{p-p}. The fraction of emission current intercepted by the focus electrode and insulator before reaching the anode was kept below 5% by increasing the diameter of the focus aperture to 2 µm. Focused spot size is plotted against anode distance for fixed focus potential in figure 3. Spot size is insensitive to gate voltage for fixed focus bias, suggesting that DC focus bias may be adequate for display applications.

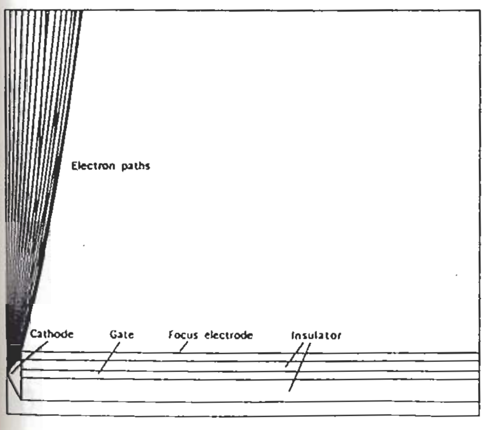

Figure 6. Close-up view of an aperture-focused field emission tip.

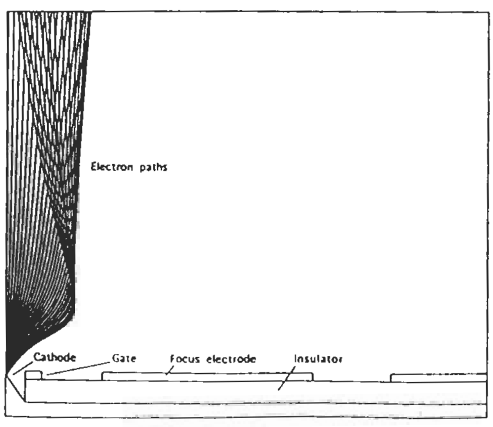

Figure 7. Close-up of a gated tip with a concentric focus electrode.

Concentric Focus

Figure 7 shows calculated electron trajectories from a gated field emission tip with a concentric focusing electrode. The gate drive characteristic and spot size are plotted in figures 2 and 3. The focus electrode is negatively biased. The prototypical gate drive is 40 V_{p-p} and is independent of focus electrode bias and spacing. Increasing the distance between the gate and focus electrodes from 2 to 5 μm had no significant effect on either the drive characteristic or spot size. The effects of neighboring tips were investigated by a worst case model having additional concentric electrodes placed every 15 μm and biased at the gate potential. The drive characteristics and spot size were unchanged when the optimum focus voltage was adjusted.

CONCLUSIONS

The maximum anode voltage of high resolution field emission displays has been limited to less than one kilovolt. Focusing the electron beams from field emission cathodes could allow wider anode-cathode gaps without loss of resolution, permitting higher anode voltages and a broader selection of phosphors. The technique of adding an aperture electrode for beam focusing can yield exceedingly small spot sizes (on the order of 10 μm, even at anode distances exceeding 1 mm which could support several kilovolts of potential drop) and acceptable dielectric stress, but the gate and cathode drive voltage is found to increase significantly (≈30%) over the unfocused case. A concentric electrode design in which the focus electrode lies in the same plane as the gate demonstrates similar spot sizes but with half the increase in drive voltage. A worst-case analysis suggests that electrical breakdown between the electrodes can be controlled by a modest increase in tip-to-tip spacing. This design offers many benefits over the aperture focused design: reduced gate capacitance, higher anode collection efficiency, lower gate drive voltages, and simplified fabrication. Experimental work and process design are now required to optimize the design for flat panel displays applications.

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