IMPROVED FIELD EMITTER CURRENT DENSITIES AND STABILITY THROUGH THE APPLICATION OF A PROPRIETARY PROCESS

CONTRACT MDA972-92-C-0033
QUARTERLY REPORT #3 September - November '92

I. INTRODUCTION

As detailed in the previous reports, the necessary current density (60 A/cm^2), linear current density (3 mA/mm) and stability (> 2 days) to meet the contract goals (at least theoretically) have been achieved. The next step is to fabricate three terminal devices to demonstrate the remaining contract goal - a one GHz current gain cutoff frequency (f_t).

Unlike the traditional Spindt-type of emitter where, because of the circularly symmetric nature of the gate, the electrons can be emitted to an anode spaced at quite large distances away, the planar emitter-gate structure used for the single-crystal approach necessitates an anode spacing on the order of several microns to prevent a significant fraction of the emitted electrons from being collected by the gate. Hence the need to fabricate the 3-terminal devices monolithically.

This report details the electron trajectory simulations needed for proper design of the three-terminal devices.

II. DESIGN CONSIDERATIONS

The addition of a third electrode to enable f_t to be measured raises the following questions: Should the third electrode, like the emitter and the gate, also be single-crystal to preserve the single crystal advantages enjoyed so far for the two-terminal structure? Where should the anode be placed so as to attract all of the emitted electrons?

Unlike the Spindt type structure where electrons are emitted (at least ideally) perpendicular to the gate electrode and because of balanced symmetry are not attracted to the gate, the planar scheme used for the single-crystal approach emits the electrons toward the gate and, unless influenced by strong fields from the anode, will all be collected by the gate. This has been empirically observed by comparing the electron collection efficiency of both the single-crystal edge structure with Spindt-type silicon point emitters supplied by Northeastern University. Using a 5 mil wide gold ribbon anode spaced some tens of mils away, virtually all of the silicon emitter electrons can be collected by the wire, while only a few percent can be collected from the edge emitter. Fig. 1 shows a curve tracer plot of the gate current for the silicon emitters, showing the gate current drop to zero as the anode voltage is increased and attracts a larger percentage of the electrons. For the edge emitter, it thus seems reasonable that the anode must exert field strengths on the order of that for the gate in the vicinity of the emitter tip to prevent gate collection. This means that the anode must be in close proximity to the emitter and hence fabricated monolithically on the same device structure. This requirement needs to be met anyway for the sake of frequency performance. To prevent transit-time degradation of the frequency response, an analysis

shows that the anode should be within 1000 microns for 1 GHz operation and within 100 microns for 10 GHz operation.

With the anode so close, should it be single-crystal also in order to not compromise the integrity of the total structure? Although ways of achieving a single-crystal anode vertically above the emitter-gate gap have been envisioned using various layered AlGaAs/GaAs combinations, to develop this more complicated technology is out of the scope of the level of effort of this contract, and it probably is not needed anyway.

Two schemes for anode placement are shown in Fig. 2. Fig. 2(b) shows the air bridge approach, using a technology that has been well-developed for Varian's GaAs MMICS [1]. While a Spindt-type of emitter might not fare too well with such an anode structure because of the direct path back from the anode to the emitter that ions can take (causing arcing and tip bombardment), the curved path of the electrons from the edge emitter to the anode should protect the emitter no matter what the anode outgasses.

Fig. 2(a) shows a totally single-crystal approach to the three-terminal device. The anode is fabricated along with same process that defines the emitter and gate, making a completely planar device with all 3 electrodes using the same n^+ GaAs layer. The problem with this approach is that the gate must be narrow enough to allow the inertial trajectory of the electron to carry it over the gate stripe to the anode. Trajectory simulations using version 4.0 of SIMION (developed by Idaho National Engineering Laboratory) show that the anode voltage has little effect on the electron trajectory until it reaches the gate edge adjacent to the anode. The gate screens out the anode potential when coplanar with it rather than above it. Because of the large overhangs needed (Fig. 2 of Report #2) to maintain a high breakdown voltage, the gate width must be at least 6 microns, and preferably 8-10 microns. Simulations show the trajectory length over the gate to range from 1.6 to 5.8 microns depending upon the grid size used. Using 2, 4 and 6 grids per 0.5 micron gives trajectory lengths of 1.6, 3.5 and 5.8 microns, respectively. The problem probably stems from SIMION's inability to handle the infinite fields resulting from the infinitely sharp emitter formed from one of the grid's corners. At any rate, the trajectory appears to be too short to clear the gate.

Fig. 3 shows a possible solution to the problem using a combination of Fig. 2(a) with Fig. 2(b). The air bridge prevents the electrons from intercepting the 6.5 micron gate length and yet allows them to be collected by the single-crystal anode. The spread in the trajectories represents electron emission at 0.3 eV in 22.5° angular steps from the horizontal to the vertical (to simulate emitter irregularities). At present, this seems to be the most versatile design of choice.

Fig. 4 simply shows that a vertical anode 4 microns above the emitter can easily attract the emitted electrons with reasonable values of voltage.

III. POSSIBLE EXPLANATION OF ARC IMMUNITY

While the elimination of grain boundaries and their outgassing could be expected to improve arc damage immunity at UHV, it is not clear why this should be an advantage at 10^{-6} Torr. At 10^{-6} Torr, one monolayer/sec of water vapor is incident upon the emitting surface, which would seem to swamp out any kind of grain boundary outgassing.

Assuming positive ions are generated at the point at which the electrons hit the gate surface, Fig. 5 shows that the trajectories taken by these ions do not even remotely

approach the emitter tip. The closest they come is if the gate corner is hit, and even then they land approximately 2 microns behind the emitter edge. It would seem that an arc could be sustained only when ions and electrons traverse the same path between points opposite from one another. This would occur if grain boundary edges began emitting, and would hold true for any emitter type (Spindt, edge, etc.). Only when the surfaces were completely cleaned by a UHV bake could this be suppressed. Thus, the single-crystal approach suppresses emission from undesired areas, minimizing the occurrence of arcs. Fig. 6 shows how, even with the single-crystal approach, arcs can be generated as the emission angle spreads out at the higher current densities.

IV. MINIMUM ANODE POTENTIAL

The question arose in the DARPA/NRL review meeting October 14, 15 as to whether an anode at zero volts can collect electrons emitted at ground potential. The answer is yes, as empirically verified by the Varian presentation. Fig. 7 shows the viewgraph that was presented. If the gate is recessed below the gate opening, the maximum field imparts velocity only in the direction of the anode, and the electron momentum carries the electron into the anode, even if at ground. If the gate protrudes through the hole, a horizontal component is given to the electrons so that the anode potential must overcome that of the gate before it can collect the electrons. The curve tracer data is from the silicon tips described earlier, with the collection anode being 5 mil gold ribbon spaced some tens of mils above the emitter. The threshold in anode current is undesirable because of reduced efficiency, especially important for power applications. Higher emission current results from emitter protrusion [2], but the above arguments would indicate that it is done at the expense of anode efficiency.

Despite lacking the symmetry of the Spindt emitter, the simulation shown in Fig. 8 shows how the single-crystal approach can achieve anode collection at zero volts.

V. CONTRACT SUMMARY

Through the use of electron trajectory simulation and empirical data, great strides were made toward understanding the principles behind an optimum device layout. These principles have relevancy to other approaches to vacuum microelectronic device design. So far there are no areas of concern.

Plans for the next quarter are to resolve the infinite field problem in the simulation, complete the mask design, and begin device fabrication.

REFERENCES

1. R. Majidi-Ahy, C. Nishimoto, M. Riaziat, M. Glenn, S. Silverman, S-L. Weng, Y. C. Pao, G. Zdasiuk, S. Bandy and Z. Tan, "100-GHz High-Gain InP MMIC Cascode Amplifier", IEEE J. Solid-State Circuits 26, 1370 (1991).

2. C. A. Spindt, I. Brodie, L. Humphrey and E.R. Westerberg, "Physical Properties of Thin Film Field Emission Cathodes with Molybdenum Cones", J. Appl. Phys. 47, 5248 (1976).

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Subtotal	$70,525	$58,832	52%	$112,592	$112,592	
Management Reserve						
Unallocated Resources						
TOTAL	$70,525	$58,832	52%	$112,592	$112,592	

*Budget At Completion (BAC) changes only with the amount of any scope changes (not affected by underrun/overrun)
** Latest Revised Estimate (LRE)

* ODDR&E/S&T recommends deletion of data on this page due to new budgets and revised dollar amounts.

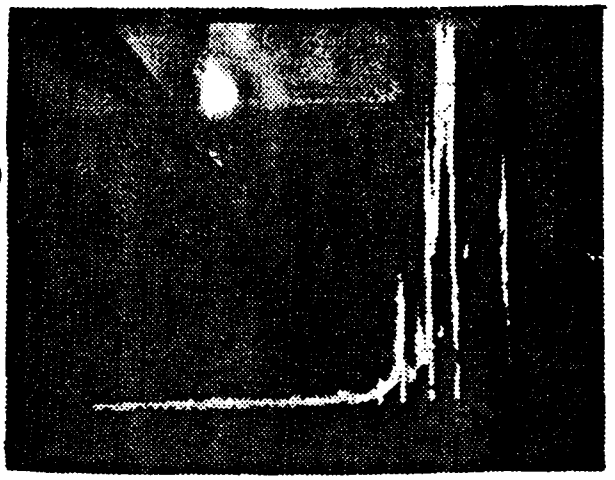

FIG. 1 Gate current decrease with anode bias (at three different values)

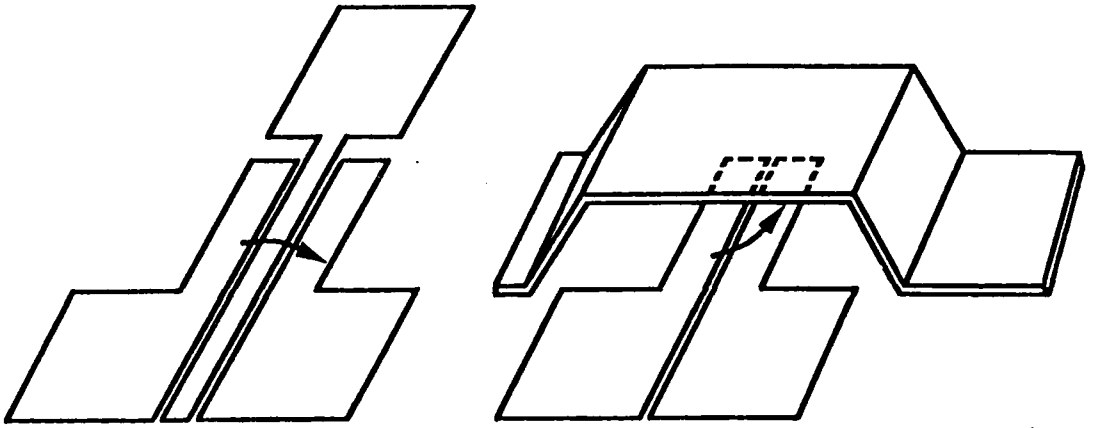

FIG. 2 Anode placement schemes

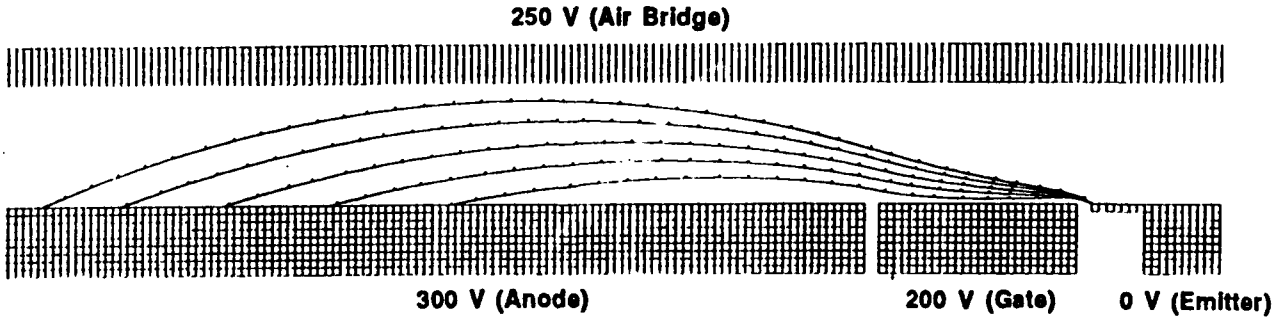

FIG. 3 Four-electrode scheme to prevent gate interception of electrons (0.3 eV in 22.5 deg. steps from horizontal to vertical)

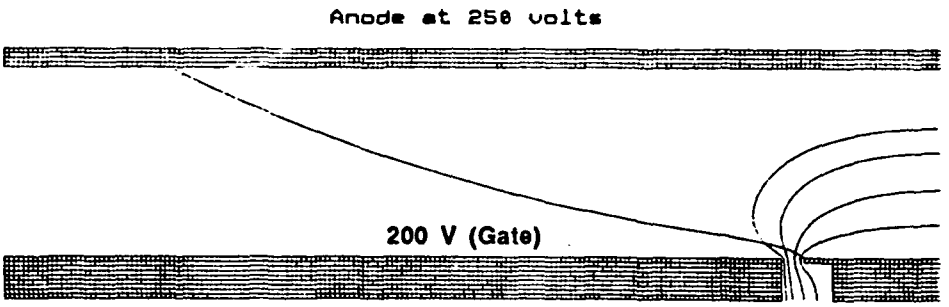

FIG. 4 Anode electrode collection

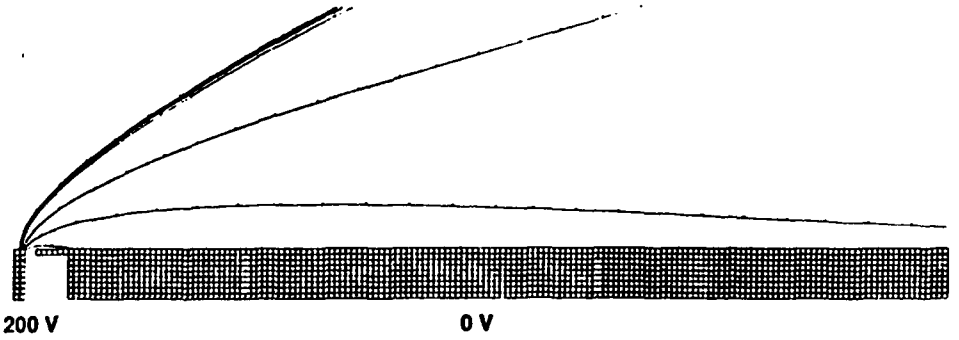

FIG. 5 Ion trajectories (0.25 micron / grid)

High Current Densities

FIG. 6 Angular dispersion of emitted current at high current densities

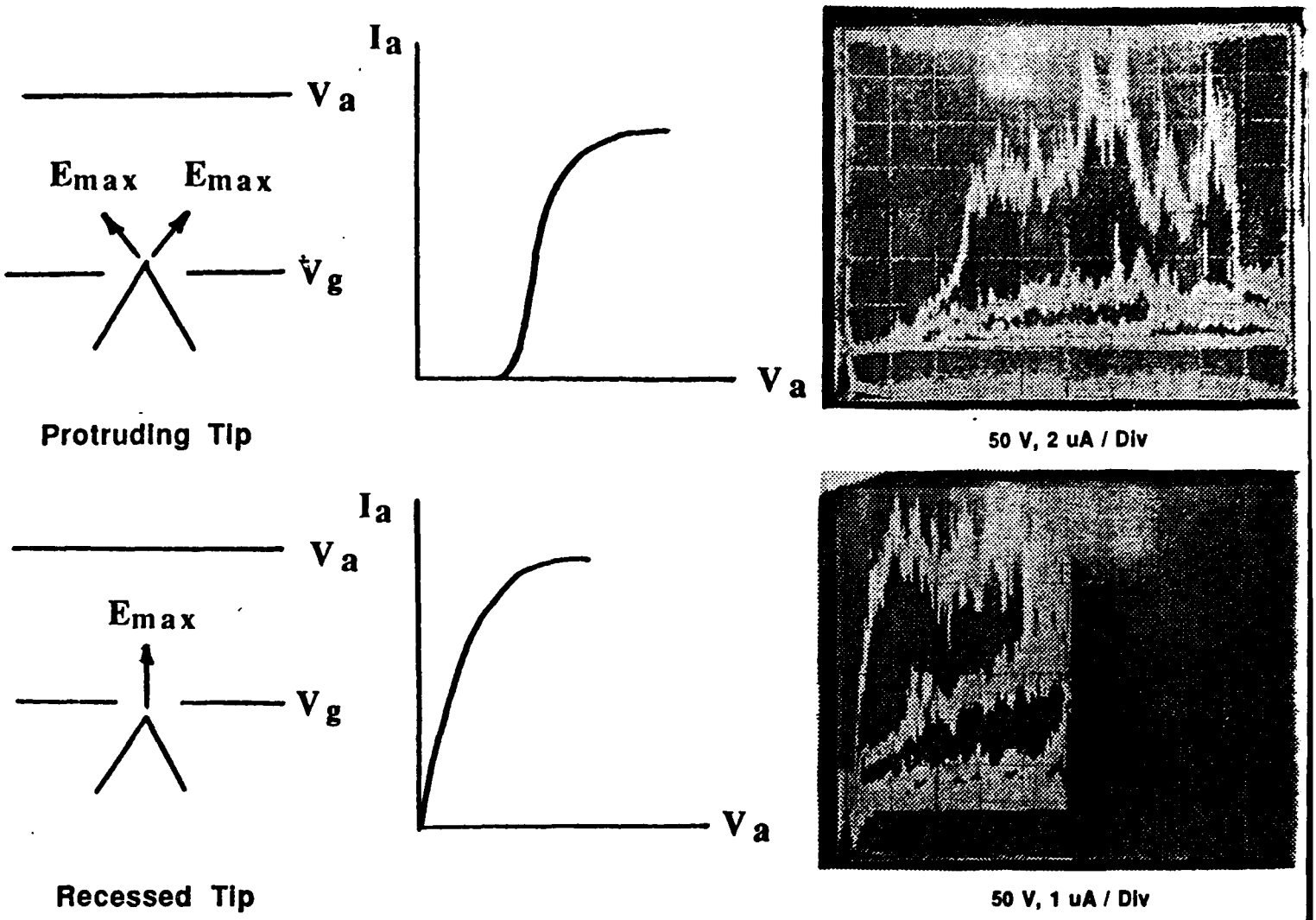

FIG. 7 Gate placement considerations

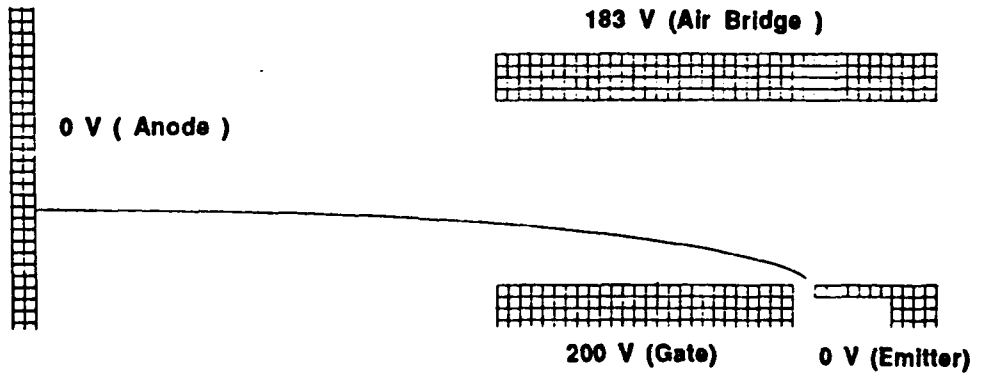

FIG. 8 Electron collection by zero-biased anode for the planar edge-emitter scheme

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