GATED FIELD-EMISSION CATHODES FOR MICROWAVE DEVICES

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Abstract

The Accelerator Research Laboratory at Texas A&M University is developing gated field-emitter cathodes for microwave and millimeter-wave applications. The cathode consists of an array of gated field-emitters which are modulated at microwave frequency to produce a fully modulated electron beam. Field-emitter structures under development include gated knife-edge arrays, reentrant cusps, and porous silicon. All feature extremely high transconductance, low noise, and rugged structure as compared to earlier field-emitter structures.

The Accelerator Research Laboratory (ARL) is developing the gigatron technology [1] for high power mm-wave linac drivers. Gigatron is based on three novel design concepts: a gated field-emitter array to produce an electron beam which is bunched at birth; configuration of the cathode and accelerating region to produce a ribbon beam to eliminate space charge and dispersion limitations; and traveling wave couplers at both the input and output to obtain optimum power transfer even across a wide ribbon beam. The present work focuses on the development of a gated field-emitter array suitable for microwave modulation in a cathode in the gigatron.

Beginning in 1976, C.A. Spindt et al. pioneered the fabrication of gated field-emitter arrays for display applications [2]. Figure 1 shows a typical Spindt tip array. These arrays have been fabricated on center-center spacings as close as 2.5 μm, and have produced electron current densities as high as 1000 A/cm^2 with a gate modulation $\sim$ 100 V. They have been operated for periods of thousands of hours, and exhibit uniform current density over the emitting array. H. Gray et al. has developed designs of tip arrays for vacuum integrated circuits and for microwave power devices [3].

Field Emission at the Cathode Surface

Spindt [2] has analyzed the measured I/V response in terms of the classic Fowler-Nordheim theory:

$$j = aE^2 \exp\left(-b\phi^{3/2}/E\right) \qquad (1)$$

where ϕ (4.5 eV for Mo) is the surface work function, and E is the surface field. In his experiments Spindt has verified Eq. (1) over six decades of cathode current. The experimentally measured quantities are voltage and current; connection to Eq. (1) thus yields a precise measure of the *effective* emitting area at the cathode surface. Spindt shows that the radius of the emitting region thus obtained is only $r_e \sim 2$ Å, a patch a few atoms in diameter. This is to be contrasted to the physical tip radius ~500 Å. Spindt and Herrmannsfeldt [4] have interpreted these results to indicate that emission occurs from atomic-scale surface features which form continuously under application of electric field. These features could be due either to mobile surface contaminants, such as an oxide layer, which produce a local reduction in work function [5], or to whiskers or bumps which protrude from the surface.

Why does emission occur from only one such microregion on each tip surface? The answer lies in an analysis of the space charge associated with the emitted current within the tip-gate region. Suppose a tip geometry such as that of Figure 1, on which emission is occurring from a particular microregion as shown. The emission produces a space charge depression which extends laterally to a distance comparable to the gap g between tip and gate. In the geometry of Figure 1, the most emissive microregion will emit, but its emission will suppress emission from any other microregion on the tip surface. This "natural selection" of one mi-

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croregion conveys two properties which create potential limits for microwave cathodes. First, the selection is intrinsically unstable: emission can jump from microregion to microregion, producing noise in the microwave emission current. Second, the emission is controlled by the field produced across the tip-base gap g, while the capacitance of the gate/base junction is determined by the gap t between the planar layers of gate and base. The power gain for a microwave cathode scales as $G \sim (t^2/s^2g)^2$, where s is the mean spacing of emitting microregions. For a tip geometry, $t \sim 1$ μm, $s \sim 2.5$ μm, $g \sim 0.5$ μm, and $G \sim 0.1$. For the ARL stripline and cusp geometries, $t \sim 1$ μm, $s \sim 0.7$ μm, $g \sim 0.1$ μm, and $G \sim 400$ – a thousandfold improvement for microwave modulation.

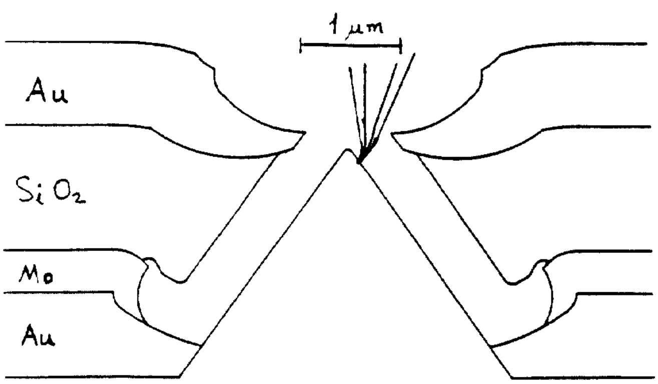

Figure 1. Typical tip geometry for gate field-emitter.

Several challenges confront the development of field-emitter cathodes for microwave and mm-wave devices. First, while the voltage required for modulation is modest, the gate-base junction is very capacitive, and hence exhibits very low impedance at high frequency. Second, recent studies of the physics of the field emission process on a tip [4] show that emission typically occurs from only one microregion, with a size scale as small as ~ 10 Å^2. Third, the input coupler must provide a low-impedance charging path to all tips on an array. ARL and the Institute for Solid State Electronics (ISSE) have developed several approaches to field-emitter arrays which address these challenges: a stripline geometry in which the emitting region is a knife-edge supported on a narrow gap from the gate (Figure 2); an inverted cusp in which the tip is replaced by a thin disc of low-work-function material supported on a cusped column above a metalized base (Figure 3); and a porous silicon cathode in which emitting channels are formed with a typical spacing $\sim$50 Å (Figure 4).

Knife-Edge Emitter Geometry

The knife-edge cathode geometry is shown in Figure 2. The emitting structure is a knife-edge which is formed by etching a thin Mo layer in a multi-laminar deposition of Au-SiO_2-Au-Mo-SiO_2-Au. The gate/base spacing is $\sim$1000 Å, and can be routinely controlled to $\pm$50 Å over an entire wafer. A gate-base voltage of 100 V produces a surface field at the knife-edge of 1.7 GV/m, sufficient to produce 0.3 μA emission current [6] from each microregion. We have established a working dielectric strength of 700 V/μm in the SiO_2 layer.

A second advantage of this design is the enhanced density of emitting microregions. Regions of reduced work function develop along the knife-edge length at a spacing roughly equal to the gap g $\sim$1000 Å between knife-edge and gate —a ten times greater emitter density than tip arrays.

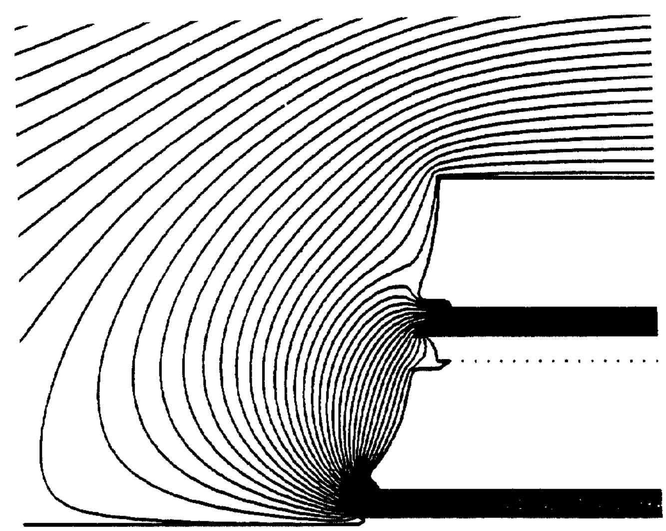

Figure 2. Knife-edge emitter geometry.

Inverted Cusp Cathodes

Figure 3 shows an array of titanium cathodes in which a plasma etch is used to create a thin metal disc supported from a column of small radius. This array was fabricated at ISSE by Legg et al. [7]. A gate layer, formed by a self-aligned deposition of SiO_2 and metal, produces a narrow gap g $\sim$1000 Å between the cathode disc and the annular gate.

The cusp geometry makes it possible to obtain a larger number of emitting microregions on the outer edge of each disc, spaced by a distance $\sim$ g $\sim$1000 Å. This structure is being fabricated with a low-work-function cathode surface (cermet) and low-impedance metalizations on gate and base.

Porous Silicon Emitting Surfaces

Yue et al. [8] have developed a novel material in which a porous layer is grown into a silicon wafer through electrochemical anodization in concentrated hydrofluoric acid. A porous silicon film made by anodizing a heavily doped silicon wafer produces pores perpendicular to the film surface through the whole porous layer with a thickness which can be controlled in the range 0.1- 10 μm. By controlling current density and anodization time, the diameters of pores can be varied from 10 Å to 100 Å with pore density from 10^8 to 10^{11} pores/mm^2. The porous layer is then fully oxidized in a thermal oxide process. At the interface between porous SiO_2 and bulk silicon substrate, an extremely sharp silicon tip is formed beneath each pore.

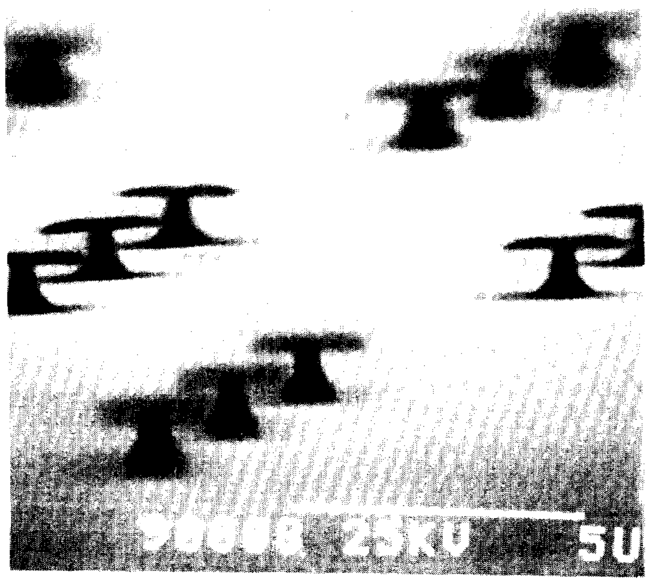

Figure 3. SEM micrograph of inverted cusp cathode array.

During the past year diode arrays of porous silicon have been fabricated at ISSE and the d.c. Fowler-Nordheim response has been measured [3]. The diode employed the above emitters while metal deposited on the surface of the oxidized porous silicon film served as the anode. The turn-on voltage of these diodes was shown to be as low as 3 to 4 volts. An emission current of 25 A/cm^2 can be produced by a 10 V modulation. The I-V characteristic follows the Fowler-Nordheim relation over three decades of current and the I-V relations are stable with temperatures ranging from 25°C up to 250°C. The immense number of independent emitter channels results in an extremely low-noise emission current – a key requirement for mm-wave applications.

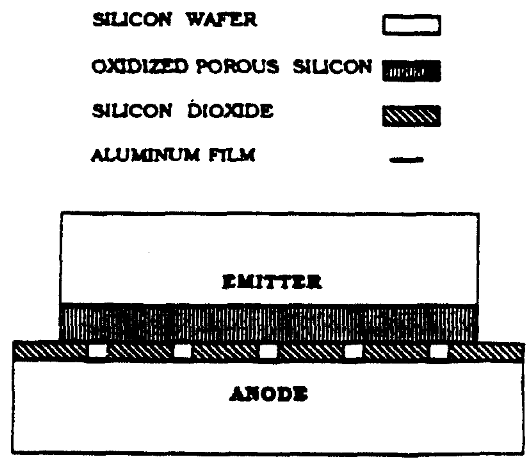

Figure 4. Diode test geometry for porous silicon field-emitter cathode.

We are developing gated microwave cathodes using these three design approaches. During the next year we will evaluate their performance and proceed to microwave testing for power tube cathodes.

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References

[1] P.M. McIntyre *et al.*, IEEE Trans. Plasma Sci. **26**, 2581, 1988.

[2] C.A. Spindt *et al.*, J. Appl. Phys. **47**, 5248 (1976).

[3] D.J. Campisi and H. Gray, Proc. Mat. Res. Soc. Meeting, 1986.

[4] W.B. Herrmannsfeldt *et al.*, "High-resolution simulation of field emission," Third Int'l Conf. on Charged Particle Beams, Toulouse, France (1990).

[5] I. Brodie, Surface Science **70**, 186 (1976).

[6] K. Ken Chin and R.B. Marcus, J. Vac. Sci. Technol. **A8**, 3586 (1990).

[7] J.D. Legg *et al.*, "Fabrication Process for Field Emission Structures," submitted to Vacuum Microelectronics Conference '90.

[8] W.K. Yue *et al.*, "Oxidized Porous Silicon Field Emission Devices," SSEI preprint 1991.