MICROELECTRONIC APPLICATIONS FOR RF SOURCES AND ACCELERATORS

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Abstract

Lithographic microfabrication techniques have been applied to the development of cathodes. In this paper, we limit the discussion of microfabricated cathodes to gated field-emitter arrays, ferroelectric and microminiature therm-ionic vacuum cathodes. These cathodes have made significant advancements in the last few years. They share in common the potential of being temporally and spatially modulated at high frequencies by low voltages with low input power requirements. These properties not only provide opportunities to improve rf power sources and accelerators, but also provide opportunities to make new commercial products.

I. INTRODUCTION

Various lithographically fabricated cathodes are emerging with potentially exciting characteristics for rf power sources and accelerator applications. In this paper, we will discuss three cathodes produced by microfabrication methods: gated field-emitter arrays (FEAs), ferroelectrics and microminiature thermionic vacuum (MTV) cathodes. The emission mechanism for each of these devices is different. Significant advancements have been made in these cathodes in the last few years, and each cathode has its own advantages, disadvantages and applications for which they are best suited. These cathodes also have the potential for major commercial applications. Vast opportunities still exist for additional research in this area.

These microelectronic cathodes share some common potential properties. In some cases, future development is required to reach these potentials. (i) The emission from these cathodes may be temporally and spatially modulated. (ii) The modulation frequency may be high. (iii) The voltages that are required to drive the modulation may be less than 100 V. (iv) The power that is required to drive the modulation may be low.

II. GATED FIELD-EMITTER ARRAYS

Gated FEAs have been under development for almost thirty years. They are based on the principle of field-emission, in which electrons tunnel through a surface potential barrier reduced by the application of high (3-6$\times 10^9$ V/m) electric fields at the solid-vacuum interface. A sche-matic of the field-emission model is shown in Fig. 1. Field-emission was first derived by Fowler and Nordheim,[1] who found the relation

$$I \propto E^2 \exp(-b/E), \qquad (1)$$

where I is the emission current, E is the electric field on the surface and b is related to the work function of the material. Current from field-emission has sharp turn-on and a sharp rise.

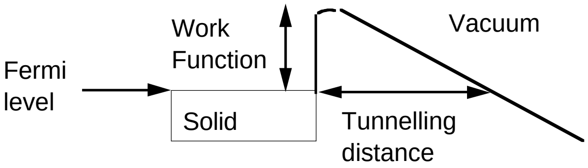

Figure 1. Schematic of field-emission.

For field emission devices to be practical, the emission has to be controlled by modest gate voltages. This can be accomplished by utilizing field enhancement at sharp corners and points and by placing the extracting electrode close to the emission site. This was first achieved by C. A. Spindt at SRI in the late 1960s by applying microfabrication technology, including thin-film deposition, photolithography, electron lithography, and wet and dry etching processes.[2] Using these techniques, Spindt fabricated an array of nearly-identical molybdenum (Mo) cones on silicon (Si) substrates. The grid or gate electrode is insulated from the substrate by silicon dioxide (SiO_2), as shown in Fig. 2. Recently, Spindt[3] fabricated FEAs with gate opening diameters as small as 0.3 μm, with tip-to-tip separation of 0.5 μm. These tips emitted on average 3 μA per tip at a gate voltage of 45 V.

A wide variety of field-emitter arrays have been developed. The most common emitter shapes are cones, wedges, edges and cones on columns. The most often used emitter materials are metals (Mo or W), semiconductors (Si and GaAs), diamond, single-crystal tungsten fibers formed by eutectic composites and graphite. Three examples will be given below.

At MIT/Lincoln Laboratory, the holographic method[4] was used to pattern gate openings as small as 0.16 μm in diameter with a tip-to-tip separation of 0.32 μm. The emitter is formed by vapor deposition similar to the Spindt approach. They measured on average 1 μA per tip at a gate voltage around 30-35 V.

MCNC has been developing silicon field emitters in the shape of cones on columns,[5] see Fig. 3. Emitter heights from 0.5 μm to 10 μm with approximately 1 μm gate diameter have been demonstrated. The thick insulator decreases the capacitance between the gate and the substrate. Average currents as high as 30 μA per tip were measured at a gate voltage of 85 V.

At Varian, single crystal GaAs edge emitters with an air-bridge have been fabricated (Fig. 4). Among its many good qualities such as an emitter material,[5] single crystal GaAs can provide more uniform edge emission and does not require ultra high vacuum. Varian has fabricate structures with emitter to gate distances of 0.3-0.4 μm. The air-bridge can be used to guide the electrons away from the gate (if anode voltage is low) and can

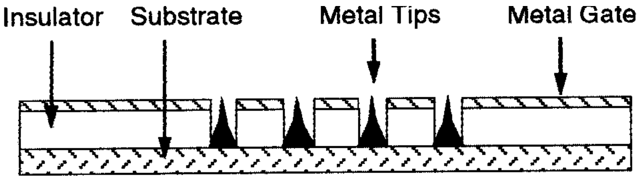

Figure 2. Schematic of Spindt cathode.

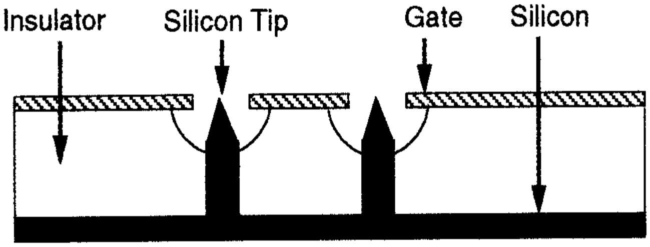

Figure 3. Schematic of MCNC silicon cones on column field-emitters.

protect the emitter edge from back-ion bombardment.

Some of the properties of FEAs that encouraged their development through out the years are: (i) The electron emission can be turned on with low gate voltages, and (ii) the emitters can be x-y addressed. These properties are appropriate for the development of flat-panel displays. Coupled with the potential visual quality of a CRT, low power consumption and low cost, the field-emitter display is emerging as a serious contender in the large market of flat-panel displays.[7] Many field-emitter display demonstration models have now been developed throughout the world.

The first successful microwave experiment utilizing FEAs was in a gyrotron oscillator built by M. Garven for her Ph.D. thesis, completed in 1994.[8] She designed the gun such that the FEAs are shielded from back-ion bombardment. The electron beam was accelerated up to 40 keV with beam power up to 1 kW. The FEA life times approached 100 hours. She measured 50 db power gain in the DC mode and operated in a gate modulated pulsed mode up to 1 kHz.

The development of a density modulated wideband inductive output amplifier in the 1-10 GHz regime with moderate power levels utilizing FEAs has been advocated primarily by R. K. Parker.[9] Inductive output amplifiers, where the rf output circuit is separated from the beam collection electrode resulting in an increase of power and bandwidth, was first proposed by Haeff and Nergaard in the 1940s.[10] The klystrode^{TM}, also an inductive output tube, was developed by Sharder and Preist.[11] It uses a cavity-driven cathode-grid region to form a modulated electron stream that is then accelerated in a high-voltage electron gun. Density modulated beams were shown to be capable of producing microwave power more efficiently, in a more compact size and at a higher power than velocity modulated devices.

The frequency, f_T, at which the short-circuit current gain attains unit magnitude, is often used as an estimate for the frequency of operation. It is defined as

$$f_T = (\Delta I/\Delta V)/C_{in}, \tag{2}$$

where ΔV is the change of the gate voltage, ΔI is the resultant change in emitted current and C_{in} is the input capacitance.

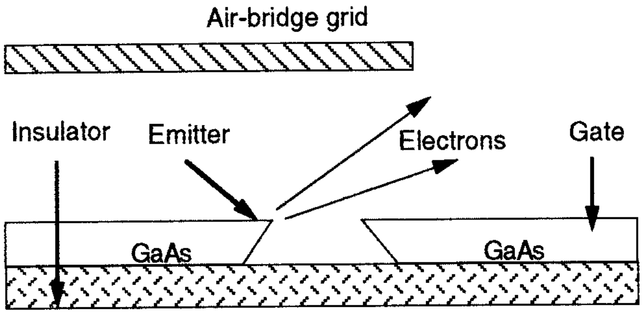

Figure 4. Schematic of Varian single crystal edge emitter with air-bridge.

The use of FEAs in an inductive output amplifier has many advantages:

i. The frequency of operation is not limited by the distance between the emitter and the extracting grid, which is typically less than 1 μm.

ii. Fowler-Nordheim field-emission has high transconductance, $\Delta I/\Delta V$. Reduction of ΔV reduces input power and an increase of ΔI increases output power. Thus, high transconductance leads to high gain.

iii. Various FEA designs and fabrication methods have steadily decreased the input capacitance. Decrease of C_{in} increases the frequency as shown by Eq. (2). Decrease of C_{in} also decreases the input power requirement and thus increases the gain.

iv. FEAs have demonstrated high current densities,[12] up to 1 kA/cm^2. High current density improves the beam propagation.

Currently two emission gated microwave amplifiers are under development which have the same objective but use slightly different approaches, i.e., twystrode and klystrode. The common objectives of the two microwave amplifier programs are: frequency of operation at 10 GHz, with 50 W output power, 10 db gain, efficiency of 50% before energy recovery with electron beam energy of 2.5 keV, to be completed by early 1997. The preliminary designs under consideration are hollow beams with peak current about 160-170 mA to be confined by a high axial magnetic field of 1-5 kG. The interaction length of the tubes will be approximately 1 cm with radius much less than 1 mm. The designs have to be somewhat flexible to accommodate various FEAs from different suppliers.

The twystrode tube will be developed in the Electronics Science and Technology Division of the Naval Research Laboratory under the guidance of R. A. Parker. A series of twystrode experiments has been performed by M. A. Kodis with other types of cathodes to establish the understanding of the physics of the twystrode.[13] For the emission gated twystrode amplifier experiment, a variety of field-emitters will be procured.

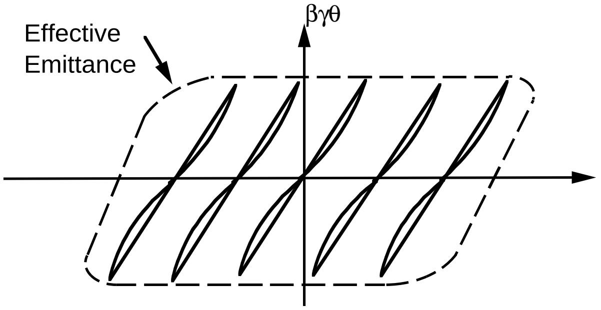

Figure 5. Schematic of normalized emittance of an array of field-emitters.

The Klystrode tube is to be developed by Varian. The FEAs are to be supplied by SRI, MIT/Lincoln Laboratory, MCNC and Varian.

The FEA requirements for the 10 GHz emission gated microwave tubes are very demanding.

(i) Currently, FEAs have only demonstrated beam modulation at 1 GHz. Optimism that beam modulation can be achieved at 10 GHz is based on (a) verification of the concepts to be used in the design of 10 GHz FEAs and (b) the development of new and improved processing techniques. Modulated beam at high frequencies may also be obtained by methods other than gate modulation.[14]

(ii) Back-ion bombardment may be prevented by proper tube design. This was demonstrated by the gyrotron experiment. The tubes must be designed such that the ions will be directed away from the FEAs. For the Varian GaAs edge emitter, the air-bridge also protects the emitter.

(iii) For uniform emission and tip protection, a resistive substrate is commonly used. However, this method cannot be used for high frequency gate modulated emission because it would reduce the transconductance. For the 10 GHz experiments, improvements in fabrication and reductions in the size of the array ($<< 1$ mm^2) will increase the possibility of finding good chips.

(iv) Emittance is an issue to be addressed in the next generation of experiments. A large magnetic field is required to confine the beam in the two present experiments. However, this is not a long term solution because of the size and weight introduced by the magnet. The normalized emittance of a single cone field emitter is very good,[15] on the order of 10^{-4} π mm-mrad calculated by EGUN2.[16] The emittance is a function of the gate voltage and the field-emitter geometry. The phase space diagram of the normalized emittance associated with a single cone field emitter tip is in the shape of a propeller, shown in Fig. 5. The effective normalized emittance of an array of field-emitters is the area enclosed by the dashed curve in the phase space diagram.[17] Reduction of the normalized effective emittance can be accomplished by fabricating lenses at each emitter, decreasing gate diameter to decrease the gate voltage and/or lowering the work function of the emitter to decrease the gate voltage. The resultant reduced effective normalized emittance is shown in Fig. 6. Various lens configurations have been simulated[17,18] and experimentally attempted.[18,19] Extensive fabrication development effort is still required to develop field-emitters with integrated lenses.

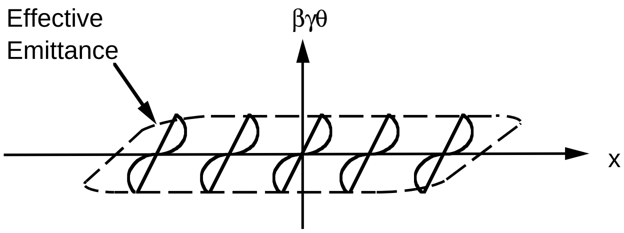

Figure 6. Schematic of normalized emittance of an array of field-emitters with lenses.

The demand of the FEAs for microwave and accelerator applications is challenging because of the high current density, high frequency and high voltage requirements. If the two proof-of-principle twystrode and klystrode experiments are successful, it would be a significant advancement in the field and would lead the way for high power devices.

The gigatron[20] is a high power amplifier concept that can reduce the space charge effect of high current density by the utilization of a ribbon beam generated from spatially and temporally modulated emission. It is compact and has high efficiencies. Originally, FEAs were the only potentially available cathode. Advancements in emission gated cathodes towards high current density and high modulation frequency may someday enable the realization of the gigatron concept.

III. FERROELECTRIC CATHODES

The development of ferroelectric material for use as a “strong” emission cathode started in 1987 when Gundel and co-workers reporting high current densities of more than 100 A/cm^2 in the absence of an external extraction field, after its discovery at CERN earlier in the year.[21] The most commonly studied ferroelectric cathodes are composed of lead lanthanum zirconate-titanate (PLZT) and lead zirconate-titanate (PZT or LZT). These ceramic materials can be polished to a thicknesses of 50 μm to 1 mm, with lithographically patterned electrodes on one side and a blank electrode on the other.

Large polarization vectors can be formed inside the ferroelectric. The initial value of P_s is obtained by prepoling a ferroelectric sample at high temperature under the influence of a modest dc electric field. Each P_s domain is related to the electric field by a hysteresis, shown in Fig. 7. Ferroelectric emission is different from classical thermionic, field, secondary or photo emissions. A simplified schematic of the emission process is shown in Fig. 8. The conceptual model shown assumes the sample is represented by a single-domain structure with two possible directions of the polarization vector P_s.

In Fig. 8a., the polarization is set up such that the polarized charges on the surface are neutralized by screening electrons and screening holes. When the electric field of sufficient strength is suddenly switched, the polarization vectors will switch. For submicrosecond polarization switching, the screening electrons will be emitted,[22] before the screening charges can flow away over the surface or through the bulk of the ferroelectric material, shown in Fig. 8b. The spontaneous polarization[23] can be as large as 20 μC/cm^2 resulting in the accumulation of a screening

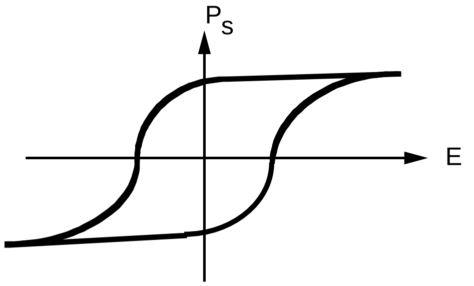

Figure 7. Hysteresis of ferroelectric materials.

charge density of 10^{18} electrons/cm^2.

The voltage required for switching of the electric field E is shown to be dependent on the thickness of the ferroelectric. For ferroelectric samples 1 mm thick,[23−25] the amplitude of the voltage pulse usually has to be greater than 1 kV with pulse lengths ranging from 100-1000 ns. The voltage pulses required to switch thinner ferroelectrics are less: (i) 100 μm thick[26] PLZT requires 300-400 V, (ii) 30-45 μm thick[27] PZT requires 75 V and (iii) 1 μm thick[26] PZT requires 10-40 V.

The polarization switching can also be produced by mechanical pressure pulses, thermal heating and laser illumination. Enhanced laser-induced emission from ferroelectrics is different from photoemission, because strong self-emission of energetic (> 10 keV) electrons was observed without an extraction field, and a threshold laser energy is needed.[28,29] Laser induced emission requires regular polarization switching in order to maintain a constant emission level. Otherwise, emission decays after some tens of pulses toward zero. The details of laser induced emission has not yet been satisfactorily explained.

The ferroelectrics are robust ceramic materials.[21] The ease of use is comparable to the best metallic cathode. They can be touched and transported through air. They do not need a good vacuum so they can work in a low-pressure gas or plasma. This emission mechanism is unique and has properties appropriate for rf sources and accelerator applications.

The current density from ferroelectrics could be high, for example, 100 A/cm^2 at CERN[21] and 70 A/cm^2 at Cornell.[25] Current density was reported to be as much as two orders of magnitude larger than the Child-Langmuir limit. One explanation is that the electrons are emitted with high energies (250 eV at MCNC[26] to 10 keV at CERN[28]).

High normalized beam brightness was reported[23] from an LTZ-2 disk. A gate voltage pulse of 1-2 kV was applied across a 1 mm thick disk 2.5 cm in diameter. For an anode voltage of 10 kV, the detected current was 15 A. The normalized emittance is 5 mm mrad and the normalized beam brightness is 1.2×10^{11} A/m^{2}rad^2, which exceeds the brightness of thermionic cathodes.

Ferroelectrics may potentially be very useful for accelerators and rf sources. Again, ferroelectrics may also have wide commercial applications.[21] For the ferroelectric to be practical as a large area cathode, the turn-on voltages have to be reduced for obtaining the desirable current density. Ferroelectric formed by thin film deposition is under development at MCNC to obtain large area, thin ferroelectrics.[26] Ferroelectrics provide many research opportunities.

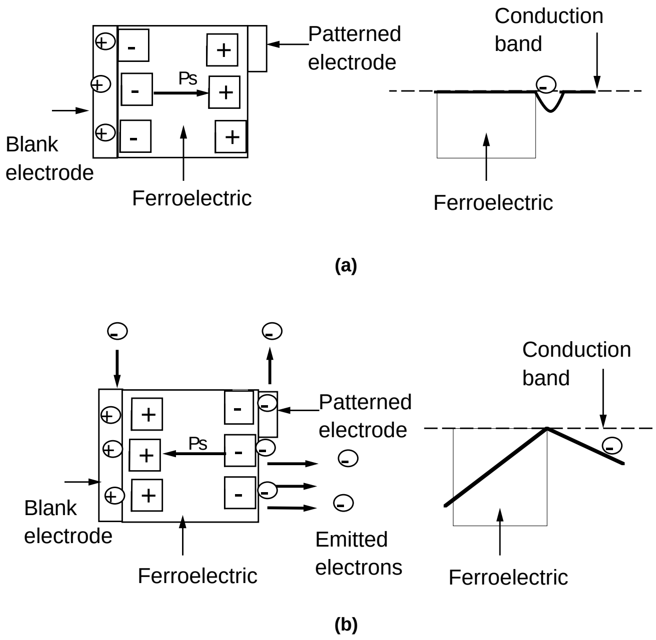

Figure 8. Schematic of ferroelectric emission mechanism: (a) no emission and (b) emission.

IV. MICROMINIATURE THERMIONIC VACUUM (MTV) CATHODE

Thermionic cathodes can also be miniaturized and large arrays of them can be fabricated so that they can be controlled spatially and temporally with low voltages.[30] A thin tungsten filament coated with low work function material suspended as an air-bridge can be heated to high temperatures by applying a low voltage across the filament. For a filament $15 \times 30 \times 1.5$ μm^3 in size and input power of 70 mW, 16 μA of current was collected by a planar anode at 100 V at a distance of a few microns from the cathode.[30] The advantages of the MTV cathode are the small size of individual components, ruggedness, radiation hardness, environmental and temperature insensitivity, the short distance between the cathode and grid, and the small capacitance between the cathode and the grid. MTV may be able to go to high frequencies, but the current density will not be as high as with FEAs.

V. SUMMARY

In summary, microfabrication methods have introduced exciting cathodes, each with its best suited applications. (i) FEAs have been under development for almost thirty years. FEAs will be entering the commercial market in the application of field-emitter displays. The FEA performance requirements for rf amplifier application are challenging, but not out of reach. The first concentrated effort to develop rf amplifiers with FEAs has been launched. Successful results will initiate significant growth in this field. (ii) Since ferroelectric cathodes with “strong” emission were only discovered in 1987, some aspects of the emission processes are not yet well understood. Ferroelectric cathodes, however, are already finding their way into accelerator related applications. It is an active area of research. (iii) MTV cathodes provide more flexibility than conventional thermionic cathode. They are still in the early stages of development.

VI. Acknowledgements

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