The Oxidized Porous Silicon Field Emission Array*

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Abstract

The goal of developing a highly efficient microwave power source has led us to investigate new methods of electron field emission. One method presently under consideration involves the use of oxidized porous silicon thin films. We have used this technology to fabricate the first working field emission arrays from this substance. This approach reduces the diameter of an individual emitter to the nanometer scale. Tests of the first samples are encouraging, with extracted electron currents to nearly 1 mA resulting from less than 20 V of pulsed DC gate voltage. Modulated emission at 5 MHz was also observed. Development of a full-scale emission array capable of delivering an electron beam at 18 GHz of minimum density 100 A/cm^2 is in progress.

I. INTRODUCTION

A. Motivation

The gigatron is a project currently under development by the High Energy Accelerator Physics group at Texas A&M University [1]. It is a high-efficiency microwave power source primarily intended for use in the next generation of linear accelerators.

One of the key innovations required for the gigatron design is its cathode, which delivers a directly modulated electron beam. This improvement eliminates the need for beam bunching and greatly improves the system efficiency compared to conventional power systems that rely on d.c. electron sources.

The search for a technology capable of delivering a high-intensity, high-current electron beam at 18 GHz led our group to investigate the use of porous silicon field emission devices.

B. History of Oxidized Porous Silicon Field Emission Devices

Porous silicon is a remarkable material. By galvanically etching silicon in an HF solution, a dense array of nanoscopic pores are etched in the surface. The pore diameter and spacing are ~100 Å; the pores can be etched up to 100 μm deep with remarkably uniform cross-section. A companion paper in this conference [2] describes the morphology of porous silicon.

Dr. W. K. Yue began research on the subject of emissive oxidized porous silicon films while he was a graduate student [3]. He developed a device known as the Oxidized Porous Silicon Field Emission Diode (OPSFED) whose interesting properties led us into this area of study. In a diode configuration he obtained stable electron field emission from microtips of highly doped silicon left over from the anodization reaction that creates the porous layer. See Figure 1. Sustained diode currents of ~20 A/cm^2 were obtained with a bias voltage of ~10 V.

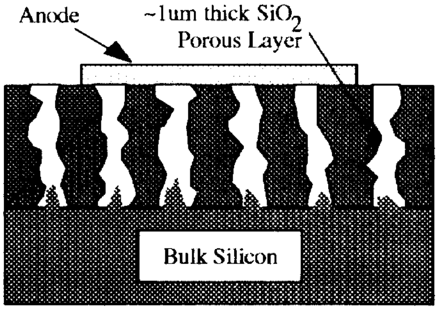

Figure 1. Schematic side view of the OPSFED.

C. Triode Development

A means of extracting the electron beam from the porous layer needed to be found in order for this approach to be useful for a gigatron cathode. No group had ever succeeded in this endeavor. The key to extraction is to provide a surface metallization on the (dielectric) porous silicon surface, which would provide a boundary conductor to effectively modulate the field in the pores. The metallization must however be thin enough to leave the pores open at the vacuum interface.

A metallization scheme developed at Ford Motor Labs by Dr. R. C. Jaklevic *et al.* was tried [4]. Approximately 40 Å of gold were applied by Dr. Jaklevic's group to the surface of four field-emissive oxidized porous silicon layers we prepared.

After metallization, the samples were diced and tested. All four samples yielded extracted emission current, and a new device was born: the oxidized porous silicon field emission array.

II. FABRICATION AND TESTING

D. Fabrication

The proof-of-principle triode prototypes were fabricated in four steps: anodization, hydrofluoric acid removal, oxidation, and metallization.

Anodization is the process by which porous silicon is formed. A silicon wafer is immersed in a solution of concentrated hydrofluoric acid and ethanol. A galvanic current is then passed through the wafer. The idea is illustrated in Figure 2.

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Process parameters include crystal orientation of the wafer, dopant type and concentration, anodization current density, HF concentration, and time of anodization. The samples we used for the triodes were p<100> Si, 0.001 Ω cm. They were anodized for 10 s under 30% wt. [HF], and the current density was varied.

After anodization the wafers were placed under vacuum for several hours to remove all residual HF from the pores so that no further silicon etching could take place.

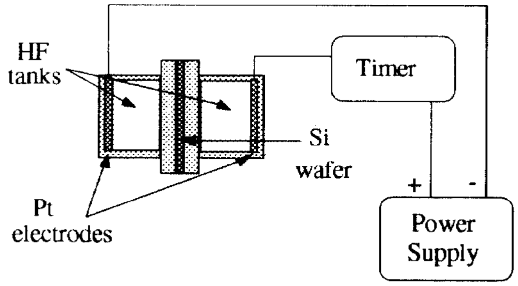

Figure 2. Apparatus to make porous silicon.

Oxidation of the films is carried out in a diffusion furnace. The temperature of the oxidation is kept well below that needed to initiate thermal SiO_2 growth in the bulk silicon.

The metallization was an evaporation at ultrahigh vacuum with the substrate held at liquid nitrogen temperature. Forty angstroms of gold were applied. This step was done for us at Ford Motor Research Labs.

The samples were laser-scribed into 2 mm squares and attached to TO-5 transistor headers as shown below. See Figure 3.

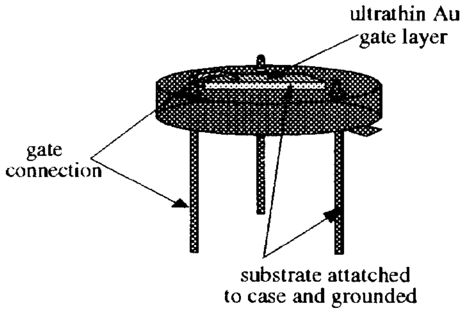

Figure 3. A field emission array ready for testing.

E. Experimental Setup

The mounted samples were placed in a vacuum chamber and pumped to a base pressure of 2×10^{-8} Torr. A curved stainless steel tube approximately 2 mm from the gate served as the collector.

A curve tracer and a variable duty cycle pulser provided gate voltage (V_g) waveforms to the devices. The collector current (I_c) and gate current (I_g) were measured as a function of V_g and collector voltage V_c.

III. RESULTS

As mentioned earlier, all four sets of oxidized porous silicon triodes produced extracted emission current. Fowler-Nordheim plots of both I_c and I_g as functions of V_g were made. Peak I_c for all traces was on the order of several hundred microamperes, and V_g was below 20 V. The curvature of the I_c-V_g plots is in qualitative agreement with the model calculations of R. Johnston [4] for emission from extremely sharp silicon tips. See Figure 4.

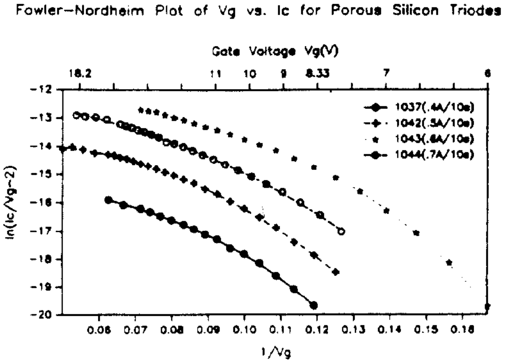

Figure 4. Fowler-Nordheim plot of collector current vs. applied gate voltage for all four samples of oxidized porous silicon field emission arrays.

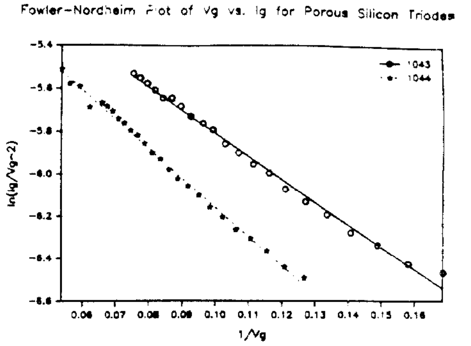

Figure 5. Fowler-Nordheim plot of the gate current vs. the applied gate voltage.

The geometry of the first triodes inevitably led to a large gate current, because many pores were obscured by the connection to the gate layer. We used this data along with the area of the gate connection to determine the emission current density. The gate connection was about 0.5 mm in diameter, and supported currents to above 2 A in pulsed mode, leading to a current density of about 450 A/cm^2. Fowler-Nordheim plots of I_g-V_g show the field-emissive nature of the gate current, as shown in Figure 5. Plate characteristics were measured by holding V_g fixed and measuring I_c as V_c was varied. A typical plate characteristic is shown in Figure 6.

Modulated gate signals were applied to the devices and emission was recorded. Figure 7 shows modulation of an array at different frequencies. The upper oscilloscope trace is the voltage signal applied to the gate, and the lower trace is the collector current read through a 10 kΩ resistor. Frequency cutoffs were consistent with the predicted RC cutoffs for the measured resistivities and capacitances of the test devices.

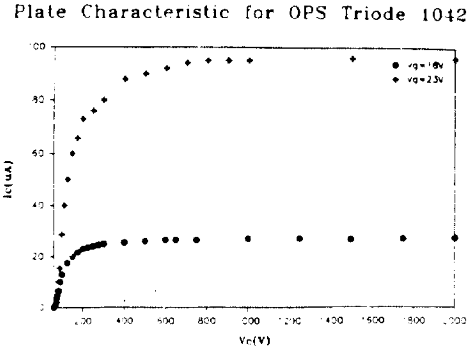

Figure 6. Plate characteristic of the oxidized porous silicon field emission array.

IV. SUMMARY

The next generation of field emission arrays will utilize a geometry consisting of alternating emission and bias feed areas. See Figure 8. This geometry radically improves power gain by blocking gate current while increasing the total active emission area. The optimum design parameters are still under consideration. Calculations indicate that a device capacitance of 20 pF/mm^2 is possible and this results in a 3 dB point above 15 GHz, suitable for gigatron operation.

The use of oxidized porous silicon is a new approach to the fabrication of field emission devices, which holds the possibility of improving both the peak output of large-scale emission arrays and the frequency at which field emission cathodes can operate.

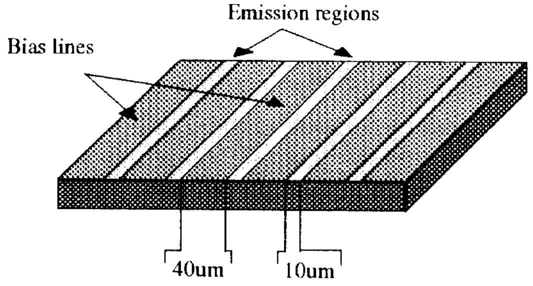

Figure 8. Geometry for the Oxidized Porous Silicon Stripline Field Emission Array.

V. REFERENCES

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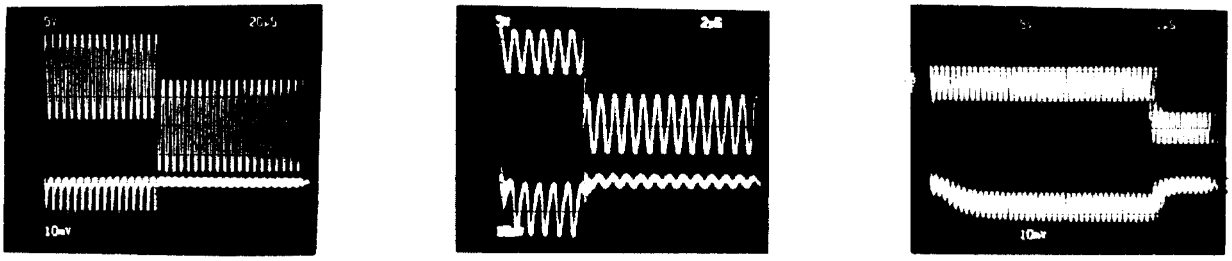

a. b. c.

Figure 7. Oscilloscope traces showing modulated emission from an oxidized porous silicon field emission array at (a) 200 kHz, (b) 1 MHz, and (c) 5 MHz.