The Oxidized Porous Silicon Vacuum Microtriode: A Revolutionary New Type of Field Emission Array*

DON D. SMITH, H. P. Demroff, T. S. Elliott, J. S. Faber, B. Lee, T. Mazumdar, P. M. McIntyre, H.-J. Trost, Y. Pang
Department of Physics
Texas A&M University
College Station, TX 77843-4242

ABSTRACT

Every year of this decade has seen an increased number of papers dealing with porous silicon (PS). The overwhelming number of these papers address issues related to the optical properties of porous silicon. An interesting property of PS that has yet received little attention is its extraordinary electroemissive properties.

The discipline of vacuum microelectronics is maturing quickly in the 1990's. With literally billions of dollars of potential market share at stake, large-scale flat-panel field emission displays have received a great deal of attention in the past few years. Other vacuum microelectronic applications include high frequency and high power devices.

Yue^[1] began studying porous silicon-based vacuum microelectronic devices in 1990. Results from a device he dubbed the Oxidized Porous Silicon Field Emission Diode (OPSFED) showed that PS offered an attractive alternative to standard field emission devices. Emission sites are reduced to near-atomic dimensions and site density is increased by six orders of magnitude. Yue, and later Madduri^[2] extracted electrons into the vacuum in a diode configuration, but no attempt to build a triode device had ever been successful.

Using a novel metallization technique developed by Dr. R. C. Jaklevic *et al.* for use in STM imaging^[3], we have successfully fabricated the first working PS-based vacuum microtriodes. Results are extremely encouraging.

Collector currents up to 700 μA were extracted across $\sim 3\text{mm}$ of vacuum with a pulsed DC gate bias of less than 20V. Simultaneous measurement of the gate current showed current densities to 700A/cm². Modulation of the emission to 5MHz was observed.

Fowler-Nordheim plots show a slight curvature, as would be expected from extremely sharp emission tips,^[4] although it is stressed that the electroemissive mechanism is as yet unknown. Fowler-Nordheim plots for OPSFED's made from the same material show an opposite curvature as predicted for emission from a

large number of sites. Density of emitters approach a true two-dimensional limit, and many applications exist if the technology can be matured.

MOTIVATION

In 1988, Dr. P. M. McIntyre invented a new type of microwave power amplifier called a gigatron. The gigatron was designed to overcome the limitations of conventional microwave power amplifiers. This is accomplished with three key innovations: a traveling-wave output coupler, a ribbon beam geometry, and a modulated microwave cathode.^[5] These innovations in the design of the gigatron will allow a 1-meter amplifier to deliver 32dB of power gain and 100MW peak power at 18GHz with an efficiency of up to 70%.

The biggest key to the success of the gigatron program is to develop its microwave cathode. A modulated electron beam completely eliminates the need for a pulser and drift region present in all conventional RF amplifiers. The choice of a ribbon beam allows extension to high beam current simply by widening the cathode. The narrowness of the beam prevents space-charge beam distortion.

Microtip field emission arrays fabricated at SRI by C. Spindt *et al.* were originally chosen for gigatron use. In 1990, these devices were tested at Texas A&M. Results of the tests showed that microtip arrays would not satisfactorily serve as gigatron cathodes. Therefore the focus of the gigatron program shifted to cathode development and the work of W. K. Yue.

POROUS SILICON ELECTRON DEVICES

Porous silicon (PS) was discovered by Uhlir and Turner in 1956.^[6] If a silicon wafer is immersed in a solution of hydrofluoric acid (HF) and a current is passed through this solution, a porous layer will be formed on the surface of the silicon. This galvanic etch process is called anodization, since the porous layer will form on the side of the wafer that intercepts the electron current.

* Supported by U. S. Dept. of Energy, Office of High Energy Physics, under contract no. DE-FG02-91ER40613.

A large body of literature exists addressing the formation of porous silicon. The result of anodization is a network of channels whose size can range from less than 10nm to over 1μm in diameter, depending on the etching conditions. Porosities in excess of 90% can be attained. Different phases of porous silicon exist: the layer can consist of a network of unconnected channels, or a microvoid type of structure can be formed. The amount of branching in the individual pores depends on the anodization conditions.

Figure 1. The OPSFED. An OPS layer is formed on the surface of a highly doped silicon wafer, then metallized under vacuum.

While earning his Ph.D. in the Electrical Engineering Department of Texas A&M University, Yue developed the first PS-based electron device, the OPSFED. This device elegantly showed the power of utilizing porous silicon in a vacuum microelectronic device. See Figure 1.

Diode current densities to 20A/cm² were produced for less than 10V applied bias. His devices produced linear Fowler-Nordheim plots, a property associated with field emission. WKB approximation for tunneling through a triangular energy barrier leads to an field-dependent tunneling current density of the form:

$$(1) \quad J = CE^2 \exp(-D/E)$$

Substitution of the relations $I = JA$ and $V = Ed$; where A is the area of emission, assuming a planar geometry with spacing d , and taking the natural log of both sides, results in the equation:

$$(2) \quad \ln\left(\frac{I}{AV^2}\right) = b\left(\frac{1}{V}\right)$$

Thus the choice of variables $\ln(I/V^2)$ and $(1/V)$ give a linear equation. Such a plot is called a Fowler-Nordheim plot, and is used extensively in the analysis of field emission devices.

Yue proposed a model in which the current was due to field emission from microtips of silicon in the bottom

of the pores (Fig. 2). More recent investigations of the morphology of PS do not support an interfacial structure of the type proposed by Yue. In fact, no detailed study of the porous-bulk interface yet exist for degenerate p⁺ porous silicon due to the incredibly tiny size and large number of pores.

Figure 2. Yue proposed that the electroemissivity he observed in the OPSFED was due to field emission from residual silicon tips at the porous-bulk interface.

Studies of porous silicon formed under conditions resulting in larger pore size show that these types of porous silicon end in ellipsoidal bowls.^[7] Modeling of emission from such a structure and comparison of such results with the experimental data presented here is greatly desired.

Experiments by Yue and Madduri showed that electron extraction from OPS into the vacuum was possible. These experiments used a diode configuration with a vacuum gap of a few microns. Madduri's setup produced up to 15μA of current for almost 100V applied bias.

In order for OPS electron devices to find a useful place in most vacuum microelectronic applications, a means of fabricating a *gated triodic structure* must be found. No such attempt had ever been successful. We felt that a metallization method developed at Ford Motor Research lab might produce such a device.

Jaklevic's method utilizes ultra-high vacuum (UHV) conditions and a cryogenic (77K) substrate temperature to evaporate extremely thin, electrically continuous layers of metal. His group has successfully deposited electrically conductive gold layers only 20Å thick with this method.

The triodes described in this paper were metallized for us by Jaklevic's group. We have constructed our own UHV cryoevaporator at Texas A&M, and process

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

development to optimize the gate layer properties is presently underway.

Having shown that this method can produce low-frequency emitters in a very straightforward manner, we now seek to determine if this technology is extensible to high frequency.

EXPERIMENTAL PROCEDURE

We began the present course of research in April 1992. In the first phase of research, we fabricated OPSFED's under a wide range of conditions. Operational devices were made from $n<100>$, $p<100>$, and $p<111>$ substrates. Anodization current densities from $10\text{mA}/\text{cm}^2$ to $150\text{mA}/\text{cm}^2$ were used. Fowler-Nordheim behavior was observed for over 80% of the samples.^[8]

Our hypothesis was that UHV cryoevaporation would leave a gate layer on the OPS surface with two important properties. First, the gold would form an electrically continuous boundary providing the electric field necessary for the initiation of electron emission. Second, we believed that the gold layer would be thin enough to leave some pores open at the surface, allowing electron extraction by the addition of a third electrode.

Four $p<100>$ silicon wafers with less than $5\text{m}\Omega\text{-cm}$ resistivity were prepared with 30wt.% HF-ethanol anodization solution. The only parameter allowed to vary was the anodization current, which incrementally ranged from .4A to .7A. Thus the anodization current density ranged from $45\text{mA}/\text{cm}^2$ to $78\text{mA}/\text{cm}^2$. This set of conditions has been found to result in an extremely porous PS morphology consisting of densely packed non-connected pores, separated by very thin walls.^[9]

Half of each wafer was made into OPSFED's and tested. The other half of each wafer was sent to Ford Labs for coating, where $40\text{\AA}$ of gold was applied. Upon return, the samples were laser scribed into $2\text{mm} \times 2\text{mm}$ square dies. To form a triode, a die was attached to a TO-5 header with conductive epoxy. Connection to the $40\text{\AA}$ gate was accomplished by first making a wirebond from one pin of the header to the case, then breaking the case connection and laying the free end of the 1-mil wire on the gate. The gate connection was secured with a tiny drop of conductive epoxy. See Figure 3.

It was expected that this configuration would display a large amount of current intercepted at the diode which was formed by this method of connection. This was acceptable, as what we wanted to see most was if the ultrathin gate would indeed allow the sustained transmission of electrons to the collector. Tunneling through the film would result in short-lived bursts of emission.

After mounting, the triode was placed on a test flange fitted with a $0.25''$ -diameter, stainless steel curved tube for a collector. The collector was placed a few millimeters from the gate. The flange was then attached to a vacuum chamber and evacuated to a base pressure of 1×10^{-8} Torr. The test setup allowed measurement of all relevant parameters.

A Tektronix Type 575 curve tracer, an HP 214A high-power pulse generator, and a Wavetek 166 function generator were used to apply various signals to the header. A HV power supply was used to maintain and monitor the collector voltage (V_C). A passive network allowed measurements of the base-gate current (I_G), the emission current (I_C), and the gate (or base) voltage (V_G).

Figure 3. OPS Vacuum microtriode prototype. The die is mounted to a TO-5 header with conductive epoxy. A 1-mil gold wire is laid on the $40\text{\AA}$ gate layer and secured with a tiny drop of conductive epoxy.

In actual operation, the base and gate were first connected to the curve tracer, and this junction was allowed to condition slowly. The device was then connected to the pulser and run at low duty cycle. The voltage was slowly increased as the collector began to receive current.

Since there was *a priori* no way of knowing the device characteristics, destructive testing was used to establish the limits of the devices. Data was taken at one level of operation, and the device would be cycled higher until the device was destroyed. Once the limits had been established, the devices could be conditioned to a limit below the destruction point.

RESULTS

Tests of the proof-of-principle microtriodes were extremely encouraging. Working triodes were made from all four samples. I-V data was taken for the

triodes, and Fowler-Nordheim plots of the collector current (Figures 4-5) and the gate current as a function of the gate voltage were made.

The triode gate results are contrasted with the OPSFED data for corresponding samples (Figures 6-7), and the triode gate Fowler-Nordheim plots are analyzed. (Figure 8.)

The triodes showed that reproducible sustained emission was indeed possible with the ultrathin gate later. Emission currents to nearly 1mA were measured. Continuous low duty-cycle runs of over 24 hours showed no loss of device performance. No special handling precautions required with standard field emission arrays are necessary. Dies stored in air for over a year showed no loss of performance.

Figure 4. I-V data for the microtriode collector current. The collector current (in mA) is shown as a function of the gate voltage (in V).

Figure 5. Fowler-Nordheim plot of the collector current vs. the gate voltage. The curvature is qualitatively of the sort predicted for emission from extremely sharp silicon tips.

It was seen that all the Fowler-Nordheim plots associated with I_c were curved. This behavior has been predicted by Johnston for emission from extremely sharp silicon emitters^[4] and by Cutler for nonplanar electrodes^[10]. This may fit well with the possible ellipsoidal morphology mentioned above, but no attempt

has yet been made to combine these theories in a PS electroemissivity model.

Interestingly enough, an opposite curvature has been predicted for Fowler-Nordheim plots of silicon tip arrays with varying tip heights. We see an analogous curvature for the results from the halves of the OPS samples that were made into OPSFED's.

Figure 6. Fowler Nordheim plots for the OPSFED data taken from the complementary halves of the original samples. The opposite curvature from Figure 4 may be due to an averaging effect from the large number of emission sites.

Figure 7. I-V data from the triode gate compared to the corresponding I-V data from OPSFED's. Low duty cycle and low pressure significantly improve OPS electroemissivity.

As mentioned earlier, it was expected that the gate connection method used in these triodes would lead to a large intercepted gate current. This was indeed the case. The OPSFED's were metallized under 10^{-6} Torr and tested with continuous 60Hz whereas the triodes were run at a base pressure of 10^{-8} Torr with a duty factor less than 10%.

These conditions greatly improved the device performance. A 1044 OPSFED produced 100mA for 43V of applied bias. The anode diameter for the OPSFED's was ~ 1.1 mm, yielding a current density of $10.5A/cm^2$.

FUTURE PLANS

In the coming year, we intend to develop a prototype gigatron cathode. Process development of this device is proceeding well. This device will have bondable gold, eliminating the use of conductive epoxy. It will also avoid having any gate current intercepted. If the process development for the gate layer can be optimized to allow full extraction of the current densities observed in the first triodes, it will be possible to fabricate a 1mm^2 device capable of 1A emission current for below 25V applied bias.

Calculations show that device capacitances below 20pF are possible, and that operating frequencies to above 20GHz are attainable, depending on the behavior of PS at microwave frequencies. More results will be forthcoming in any event.

CONCLUSIONS

Oxidized porous silicon vacuum microtriodes were fabricated and tested. Pulsed DC testing yielded emission currents to .7mA for gate bias below 19V. Gate currents to 1.4A were measured with a peak current density above $700\text{A}/\text{cm}^2$. Fowler-Nordheim analyses are suggestive of a mechanism related to the nanoscopic features of the porous silicon upon which the device is based.

Modulation of the emission current to 5MHz was observed, a positive sign for extension to higher frequencies. It was seen that optimization of the gate deposition process will be require to fully exploit the potential of this technology.

We have successfully fabricated a completely new type of vacuum microelectronic device. The promise of realizing true two-dimensional field emission arrays has come one step closer to reality. Many potential applications for this technology exist, and it may prove to be an important vacuum microelectronic breakthrough.

REFERENCES

- [1] W. K. Yue, "Electron field emission in porous silicon", Dissertation, Texas A&M University, Aug. 1991.
- [2] V. Madduri, "Fabrication and testing of oxidized porous silicon field emitter strips," Thesis, Texas A&M University, Aug. 1992.
- [3] R. C. Jaklevic *et. al.*, "Application of the scanning tunneling microscope to insulating surfaces", *J. Vac. Sci. Technol. A* 6, 448-453 (1988).
- [4] R. Johnston, "The physics of field emission in the context of vacuum microelectronics", *Surf. Sci.* 246, 64-68 (1991).
- [5] H. M. Bizek, *et. al.*, "Gigatron", *IEEE Trans. on Plasma Sci.* 16, 258-263 (1988).
- [6] A. H. Uhlir, "Electrolyte Shaping of Germanium and Silicon," *J. Electrochem. Soc.* 35 333-347 (1956).
- [7] P. C. Searson *et. al.*, "Pore morphology and the mechanism of pore formation of in n-type silicon", *J. Appl. Phys.* 72, 253-258 (1992).
- [8] D. D. Smith, "Development of an oxidized porous silicon microtriode", Thesis, Texas A&M University, to be published May 1994.
- [9] P. C. Searson *et. al.*, "The formation, morphology, and optical properties of porous silicon structures", *J. Electrochem. Soc.* 139, 3373-3378 (1992).
- [10] J. He *et. al.*, "Generalization of Fowler-Nordheim theory for nonplanar metal emitters", *Appl. Phys. Lett.* 59, 1644-1646 (1991).

In contrast, a prodigious amount of current was collected at the triode gate: up to 1.4A of current was measured at 18V in a 1044 triode sample. This current was collected on an epoxy dot $\sim 5\text{mm}$ in diameter, resulting in a current density of $713\text{A}/\text{cm}^2$.

It was found that very little collector voltage was needed to fully collect the electrons, even across the 3mm gate-collector spacing. Only a few hundred volts were required for full collection at low pressure.

Figure 9 shows the plate characteristic for the triodes. The gate current was held constant, while the collector current was measured as a function of the collector voltage. The current vanished for low collector voltage, and saturated at a few hundred volts.

Figure 8. The Fowler-Nordheim plots for the triode gate current are linear. This may be a balance of effects associated with the nature of OPS electron emission.

Figure 9. Plate characteristic for the triodes. The collector current in μA is plotted vs. collector voltage in kV .

Modulated gate signals were applied to the triodes, and corresponding modulation of the emission current was observed. Figure 10 shows a sequence of photographs of the modulated emission at 200kHz , 1MHz , and 5MHz .

It was observed in the testing of the proof-of-principle triodes that the ratio of emission current to gate current was ~ 0.001 for all samples, and is most likely related to the properties of the gate layer.

The tests were not able to determine the emission area. Therefore it is not known if this discrepancy is due to the resistivity of the gate layer giving rise to an annular region of emission, or if the gate layer blocks many pores. These issues will be dealt with in the coming months as process development of a prototype gigatron cathode unfolds.

(a)

(b)

(c)

Figure 10. Oscilloscope pictures showing the modulation at (a) 200kHz , (b) 1MHz , and (c) 5MHz . The top trace is the gate voltage and the bottom trace is the emission current.