A PROGRESS REPORT ON THE LIVERMORE MINIATURE VACUUM TUBE PROJECT*

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ABSTRACT

Using the sacrificial layer process, we are designing and building micron-sized vacuum diodes and triodes. The devices use silicon field emitters etched into the surface of a silicon wafer. The field emitters are then buryed in layers of glass and conductive polysilicon to produce the grid and anode. The last step is to remove the glass layers, leaving the free standing anode and grid with 1 to 2 µm separations.

Vacuum microelectronics are expected to be hard to more than 10^{17} neutrons/cm^2 and 10^8 Rad(Si) of gammas without sustaining permanent damage. Note that this is three to four orders of magnitude greater than the radiation levels that comparable silicon devices can withstand. Upset is expected to be on the order of 10^{11} Rad(Si)/s, compared to 10^8 Rad(Si)/s for silicon devices. Vacuum microelectronics should also be able to withstand in excess of 775 K, compared to a maximum of 650 K for the best silicon devices.

Our current work involves enhancing the sharpness of the field emitters, so that they can operate at lower voltages. Recent applications of an oxidation sharpening method has created tips with a radius of curvature on the tip of less than 10 Å.

INTRODUCTION

Miniature vacuum diodes and triodes are micron sized, electronic switching and control devices with vacuum as the active volume. They also use field emission as the electron source instead of thermionic emission as is used in conventional vacuum tubes. They are fabricated on silicon wafers using much the same processing techniques as are used for solid-state integrated circuits, making them compatible with existing integrated circuit technology. This compatibility makes possible the eventual integration of miniature vacuum tubes with existing integrated circuit components. We use the sacrificial layer technique to produce the free standing structures [1].

Experimental investigations at Los Alamos National Laboratory produced a thermionic vacuum triode on a silicon wafer with anode to cathode distances on the order of 1 mm. Radiation and thermal testing of that device produced the data shown in Table 1 [2].

While the data in Table 1 is for a larger device, we expect the micron sized vacuum triode to have a similar radiation hardness. Note that in most cases, the values for the vacuum tubes are only lower limits. This is because the researchers had to stop testing after reaching the indicated dose. Continued testing would have required an inordinate amount of resources.

FABRICATION OF THE VACUUM TRIODE

The basic device structure is shown in figure 1. First, coat the surface (100) of the silicon wafer with an isolation layer consisting of 0.5 µm of silicon dioxide and 0.4 µm of silicon nitride. The field emitters are created by etching around and behind a mask of silicon nitride that is 5 microns square and 800Å thick. We are currently experimenting with several different etches, both anisotropic and isotropic. The most successful to date has been an isotropic etch of 25 parts nitric acid, 10 parts hydrofluoric acid and 3 parts acetic acid. The tips are sharpened by growing and removing a 500 to 1000 Å thermal oxide layer. The cavity containing the field emitter is then filled with low density glass. The wafer is coated with doped polysilicon that is masked and etched to form a grid. The grid is buryed with another layer of glass and one of doped polysilicon to form the anode. Finally, we remove the low density glass using hydrofluoric acid. The resulting structure, with the free standing anode and grid, is shown in Figures 1, and 2.

Table 1. Comparison of the temperature and radiation tolerance of semiconductors and vacuum tubes.

	Semiconductors	Vacuum Tubes
Maximum Temperature (K)	600	>775
Temporary Upset (Rad (Si)/s)	10^8	4×10^{11} projected
Permanent Damage (neutrons/cm^2)	10^{13}	$>10^{17}$
(Rad (Si))	5×10^5	$>2.5\times10^8$

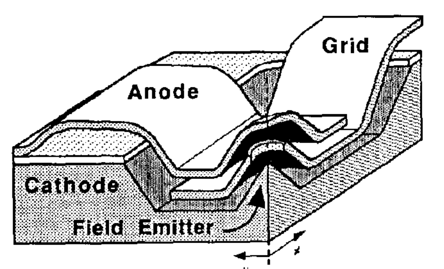

Figure 1 A cutaway section of the vacuum triode showing the field emitter, grid and anode.

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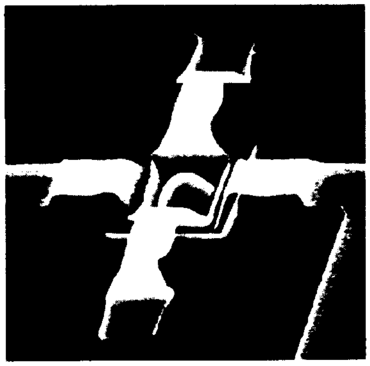

I.....25 μ.....I

Figure 2. Electron-micrograph of the vacuum triode. The horizontal structure is the grid, and the vertical structure is the anode. The field emitter is under the hemispherical section at the center of the anode.

Figure 3 shows a vacuum diode with the anode structure broken loose and flipped over. The vacuum diode is a simple variation of the triode design, in which the polysilicon grid is left out. Currently, the whole wafer must be placed in a vacuum chamber. However future designs will have the anode extend over to the edges of the hole, so that the cavity containing the triode can be evacuated and sealed.

I......20 μ......I

Figure 3 Electron-micrograph of the vacuum diode with the anode broken off and flipped over to show its underside, and the field emitter.

NEW DEVELOPMENTS

Process Hard Isolation Layer

In our initial devices, we used a silicon dioxide isolation layer to cover the substrate and isolate the bond pads that attach to the anode and grid. The long processing times required to remove the sacrificial layer damaged this isolation layer to such an extent that when wires were attached to the pads, they tended to short to the substrate. We changed the isolation layer to silicon nitride, but Frenkel-Poole conduction in the silicon nitride obscured any field emission [3]. Frenkel-Poole conduction in silicon nitride is difficult to tell from field emission by the shape of the current versus voltage curve. However, it can be identified by the fact that it is bidirectional and temperature sensitive.

We corrected this problem by first coating the wafer with silicon dioxide (0.5 μm), and then with silicon nitride (0.4 μm). Bond pads placed over this isolation layer can now withstand wirebonding without shorting and can hold off over 500 V without significant leakage (5.9 x 10^{-9} A/cm^2 @ 300V, 1.2 x 10^{-3} A/cm^2 @ 500V) or breakdown.

Anode Stiffening

While testing some vacuum diodes, we applied 300 V across then and observed anomalous currents that would erratically tum on and off. It appears that the electrostatic attraction between the anode and the substrate was sufficient to bend the anode down until it touched the substrate, causing a short and also collapsing the field. When the field collapsed, the anode would spring back and break the connection, creating the switching of the current. To correct this problem, we are stiffening the anode by thickening it, and are currently working on the emission rate of our field emitters to make them operate at a lower voltage.

Field Emitter Design

Our initial sets of field emission tips were created by anisotropic etching of silicon with ethylenediamine-pyrocatechol-water (EPW). EPW is hard to control, and resulted in tips with a radius of curvature on the order of 1000 Å. We changed to potassium hydroxide buffered with secondary butyl alcohol and water (KAW), which is slower, but much more controlled, resulting in tips with a curvature of less than 500 Å. Using a field of emitters created with this process, we achieved field emission with an applied voltage of 40 V across a 2 μm vacuum gap (Figure 4).

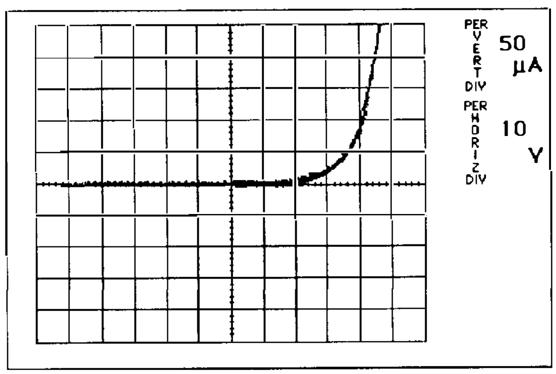

Figure 4: Current versus voltage curves for a field of 10,000 to 15,000 field emitters spaced two microns from an anode.

To further increase the emission rate, we are currently working with an isotropic etch of 25 parts nitric acid, 10 parts hydrofluoric acid and 3 parts acetic acid (NHA). This etch has produced tips with a radius of curvature between 250 and 1500 Å. Field emission from fields of these tips is similar to that from the KAW tips shown in Figure 4. In a parallel, collaborative effort with Bob Marcus of Bellcore [4], these tips were further sharpened by oxidation to a radius of curvature of less than 10 Å. We have yet to test the field emission rate of these tips, but expect it to be much higher than the unsharpened tips.

MODELING

Using the combination of a two-dimensional static field modeling code, and the theoretical Fowler-Nordheim equation, we have estimated the operating characteristics of our vacuum triode (Figure 6). The curves were created by fitting the field at the tip of the field emitter, calculated with the static field

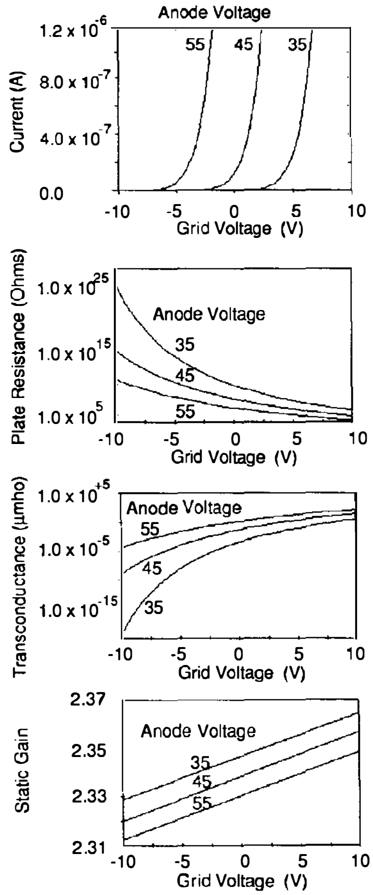

Figure 6: Theoretical current-voltage, plate resistance, transconductance and static gain curves for the miniature vacuum triode. These assume a 1.5 micron anode to cathode distance, the tip of the cathode is centered in a 1 micron radius hole, and even with the top of the grid, the emission area is 0.2 microns in diameter and the field at the tip has an additional enhancement factor of 20 due to microstructure on the tip.

modeling code, versus the voltage on the anode and grid. The resulting equation is inserted into the Fowler-Nordheim equation to calculate the current-voltage characteristics. By taking the appropriate derivatives of the current-voltage curve [1], we obtain the tube parameters. Note that these tube parameter values are not typical of those expected from more traditional vacuum tubes. The plate resistance is high, the transconductance is low, and the static gain is low. These differences must be taken into account when designing circuits for these devices.

As these calculations are based on our original EPW created tips, they need to be redone for the oxide sharpened, NHA tips, which are much sharper and of a different shape than the EPW tips. We expect to do those calculations in the near future.

CONCLUSION

Vacuum microelectronics, because they have a vacuum as their active region, are expected to be extremely hard to neutrons ($>10^{17}$ neutrons/cm^2) and gammas ($>10^8$ Rad(Si)). Upset is expected to be on the order of 10^{11} Rad(Si)/s. Vacuum microelectronics should also be able to withstand temperatures in excess of 775 K.

Using the sacrificial layer process, we have designed and built the structures for micron-sized vacuum diodes and triodes. The devices were fabricated by etching silicon field emitters into the surface of a silicon wafer. Burying that field emitter in layers of glass and conductive polysilicon. And, then removing the glass layers to leave the free standing anode and grid above the field emitter. The separation between the field emitter and the grid and anode is in the 1 to 2 μm range.

We are currently increasing the sharpness of our field emitters. Using an isotropic etch of Nitric, Hydrofluoric and Acetic acid, we have created tips with a radius of curvature of 250 to 1500 Å. Recently, in collaboration with Bob Marcus at Bellcore, these tips were sharpened using a low temperature oxidation, resulting in tips with a radius of curvature of less than 10 Å. In the near future we will insert these sharpened tips into our diode and triode structures, to produce operating diodes and triodes.

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