POINTER AND WEDGE TUNGSTEN-ON-SILICON FIELD EMITTER ARRAYS

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ABSTRACT

We have measured 20 microamperes/tip from single-tip silicon Field Emitter Array (FEA) cells made from $10^{15}$/cm$^2$ n-type silicon. The current-voltage characteristics show a linear Fowler-Nordheim relationship and do not show current saturation. These results indicate that silicon-based FEAs might be able to compete with metal-based FEAs for RF power applications. In addition, we report the fabrication of silicon-based wedge, trench, and tungsten-on-silicon FEA structures.

INTRODUCTION

Field Emitter Arrays (FEAs) are being considered for a variety of applications which span a wide range of current density, total current, array size, and electron source geometry. Interest is particularly strong in flat panel display technology and low-power RF amplifier applications which might operate up to 100 GHz with reasonable efficiency and wide-bandwidth. In addition, FEAs promise the possibility of new high current density cold cathodes for high-power electron tubes as well as microminiaturized electron guns which can be modulated at very high frequencies for applications such as pre-bunching in linear beam tubes or multibeam electron lithography. Each different application requires a different set of FEA properties. Some applications, e.g., flat panel displays, do not require high currents or high current densities, whereas other applications, e.g., high-power microwave or millimeter wave devices, need both high transconductance and high current density. Furthermore, each application has its own associated problems, e.g., back ion bombardment in linear beam tubes, which must be taken into account in the design of the FEA structure and the ability to make large, inexpensive arrays for flat panel displays.

Classical single-tip field emitters are typically made from bulk single crystal refractory metals rather than semiconductors basically for the following two reasons: (1) Metals provide about $10^{22}$ free electrons/cm$^3$ vs. $10^{15}$-$10^{18}$/cm$^3$ for semiconductors. Since the emitted current density is essentially the number of free electrons times a surface barrier transmission coefficient, and since the transmission coefficients of metals and semiconductors are comparable, metals appear to have a several orders of magnitude advantage. In fact, field emission current densities approaching $10^8$ A/cm$^2$ have been measured from metal field tips, a value which is orders of magnitude greater than that measured from free standing semiconductor field tips. (2) Refractory metals have a high melting point which minimizes tip destruction due to joule heating. Current runaway means that if the current through the field emitter exceeds a certain critical amount, joule heating (and perhaps Nottingham heating) will cause the field tip to heat up and eventually melt. Albeit that these reasons might be valid for free standing field emitter applications, different properties might be equally, if not more, important for FEA applications. For example, one might require emission uniformity, protection from current runaway, or an affordable fabrication process such as the batch processing used for making silicon ICs. These latter issues were the driving force behind recent development of silicon FEAs [1-3] and silicon vacuum transistors. Results from the first planar silicon vacuum FET [2,3] indicated that silicon might have a natural protection from current runaway, a property not found in metals. However, the recent observation of 20 microamperes/tip from single tip silicon FEAs [4] brings into question the extent that velocity saturation has on field emission from silicon. Oxidation sharpening [4,5] of silicon field tips indicated that one might obtain excellent uniformity and controllably sharp tips, also something that had been very hard to obtain in metals. Furthermore, using gaseous etching, uniformly sharp metal [7] field emitters have been made. Both of these FEAs (silicon and metal) have comparable field emitter characteristics [6,7]. Consequently, in the future the material from which FEAs are made might be determined from factors other than emission current density.

FABRICATION

Our goal was to obtain 4-sided pyramidal silicon field emitters so that we could eventually model the transport process. Previous oxidation sharpening techniques [4,5] created cusp-like field emitters which have narrow necks. We believe that narrow necks can inhibit the flow of electrons to the tip surface thereby increasing joule heating in the emitter which could cause the tip to melt [8]. Other wide angle field emitters have been made [9], but controlling the shape has been very difficult.

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Our orientation-dependent-etch (ODE) process, still considered proprietary [10], results in pyramidal point-like field emitters whose sides are silicon <111> planes. This shape has an intersection angle at the tip of about 70 degrees. The wedge-like emitters also have well formed <111> sidewalls.

The rest of the silicon processing was rather standard. The n-type <100> silicon wafers were thermally oxidized at 1000°C in wet oxygen to a thickness of about 150 nm. After the oxide was patterned and etched using reactive ion etching (RIE), arrays of point-like and wedge-like field emitters were made using a proprietary wet ODE process. A self-aligned process, similar to that previously reported [2,3], was utilized to fabricate the self-aligned extraction gates. The field emitters were then thermally oxidized using standard oxidation steps which do not create stress. This oxidation step preserves the <111> sidewall shape while it sharpens the underlying pyramid. Figures (1) and (2) are SEM photographs of the resultant FEA cell and the <111> sidewalled wedge-like FEA cell. Notice the well defined <111> sidewalls. We estimate that the radius of curvature of both the pyramid and wedge is about 100 angstroms which we feel is close to the optimum tip radius required for reasonably low voltage operation.

We also fabricated and characterized trench FEAs which are shown in figures (3) and (4). We hope that this structure will minimize back-ion bombardment effects in linear beam power tube environments. Stress oxidation sharpening was used to decrease the 90 degree angle of the emitter edges (shown on the left and right sides of the silicon trench in fig. (4)) to about 60-70 degrees in some samples. (The sharpened structures are not shown.) We modified some of the point and wedge FEAs by replacing the surface silicon atoms with tungsten using a WF6 chemical vapor deposition (CVD) process. The resultant thickness of the tungsten surface layer was 50-200 angstroms. Our motivation was: (1) Surface states, suspected of spoiling the emission energy distribution [11] and which might also cause significant Nottingham heating of the emitter, would be eliminated. (2) The surface electron density would be increased which would increase the emission capability. It would also provide a lower resistivity path to the emitting surface. We hoped for emitter characteristics comparable to bulk metal emitters.

**ELECTRON EMISSION MEASUREMENTS**

After fabrication, no special precautions were used to clean the FEAs or measurement probes. The samples were merely removed from their chip carrier containers and inserted into our standard UHV test chamber. We did not bake out the system, and no in-situ cleaning was attempted. The pressure during emission measurements was about 5 x 10^-7 torr. The measurement system was configured with 3 manipulators, each with a high value resistor (10^9-10^10 ohms) in series with the sample probe.

One of the probes was positioned directly over the FEA; it was the free-standing field emission collector. Figure (5) shows a typical current-voltage characteristic for a single point FEA cell. The measured current is to the free-standing probe. Figure (6) is a Fowler-Nordheim plot of the same data. The straight Fowler-Nordheim plot is interpreted to indicate field emission. We have also measured emission currents up to about 20 microamperes/tip in single tip, pyramidal, FEA structures, and the data also exhibits a straight Fowler-Nordheim plot. These results are consistent with previously reported data taken from silicon cusp structures [6]. Figure (7) shows typical "short life" test data of 25 days duration for a single point FEA cell. Although this plot shows typical field emission fluctuations, we have observed no permanent emission degradation.

Unfortunately, all our tungsten coated samples experienced significant degradation within a period of approximately one day. This degradation is consistent with our previous experience with other types of metal FEAs in unbaked vacuum systems.

**CONCLUSIONS**

We have measured 20 microamperes/tip from single-tip silicon Field Emitter Array (FEA) cells made from 10^16/cm^3 n-type silicon. The current-voltage characteristics show a linear Fowler-Nordheim relationship and do not show current saturation. These results indicate that silicon based FEAs might be able to compete with metal based FEAs for RF power applications. In addition, we fabricated and characterized silicon wedge, trench, and tungsten-on-silicon FEA structures. These new structures might have advantages and disadvantages compared with the classical point-like structures in some applications such as linear beam tubes.

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**REFERENCES**


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Figure 1
A pyramidal silicon point-like FEA Cell.

Figure 2
A silicon wedge-like FEA Cell with <111> sidewalls

Figure 3
Top view of a silicon trench FEA

Figure 4
A silicon trench FEA showing symmetrical emitter corners

8.7.3
Figure 5
Current-Voltage characteristics for a single silicon FEA cell

Figure 6
Fowler-Nordheim Plot for a single silicon FEA cell

Figure 7
Short "Life Test" of a Single Point Silicon FEA