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THE POTENTIAL OF VACUUM MICROELECTRONICS FOR SPACE REACTOR APPLICATIONS

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Abstract

Matrixed field emission devices have been fabricated using a modification of standard integrated circuit fabrication techniques. The emitter-to-gate spacing is fixed by the thickness of a deposited oxide and not by photolithographic techniques. Functioning triodes have been fabricated using this deposited oxide spacer approach. Measured emission current to a collector electrically and physically separated from the matrixed emission array follows Fowler-Nordheim behavior. Modeling of the potential field near the emitter and gate structures as well as the emitted electron trajectories with a two-dimensional, Poisson solver, finite-difference code was used to evaluate and improve field emission structures.

INTRODUCTION

Electronics placed in-core and near-core for space and terrestrial applications can enhance reactor performance, safety, and reliability. Unfortunately, the thermal and radiation environments found near the reactor and its shield prevent the use of commercially available electronics for instrumentation and control (I&C) and power functions. The total gamma dose and neutron fluence near the reactor and radiation shield can be up to several orders of magnitude greater than the dose and fluence for which commercially available electronics are qualified. In addition, the 570 K to 770 K thermal environment found near a reactor exceeds the 375 K operational limit of most commercial electronics. Several relatively new electronic technologies -- wide bandgap semiconductor materials and vacuum microelectronics -- are under development and may have the potential to be used as high-temperature and radiation electronics for I&C or power applications.

This paper briefly reviews the history and physics of vacuum-based electronics and summarizes the development of vacuum microelectronic devices at Sandia National Laboratories. We describe work in fabrication, testing, and modeling of vacuum electronic devices.

VACUUM-BASED ELECTRONICS

Vacuum based electronics that use cold cathode and thermionic emissions have been studied for decades. Vacuum tubes (based on thermionic emission) were the dominant electronic product world wide from the 1930s through the 1950s. They were supplanted by solid-state devices during the mid-1960s. Solid-state devices demonstrated better reliability, efficiency, integrability, and versatility than vacuum tubes. Today, vacuum electronics technology has survived only in such specialized fields as high-power and high-frequency applications. Since the mid-1980s, the electronics community's interest in vacuum electronics has sharply increased owing to advances in nanofabrication technology (the ability to fabricate micrometer- and submicrometer-sized structures in electronic materials). Although micromachining techniques in a wide variety of materials have increased the feasibility of developing reliable and versatile vacuum microelectronic products which have performance advantages over solid-state electronics, roadblocks to the successful development of vacuum-based electronics still exist.

Vacuum microelectronics based on cold cathode emission can be thought of as micrometer-sized field effect transistor (FET) devices. A simple schematic of a cold cathode triode is shown in Figure 1. Micrometer-sized emitting structures (cathodes or emitters) are fabricated so that they are surrounded by or near to grids (or gates).

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Electrons are emitted when a voltage is placed across the cathode-grid structure and are then collected by the anode (or collector) structure. Desirable features for the vacuum triode include a small size with controllable sizes for features (such as cathode tip radius or cathode tip-to-grid distance), operation at low voltages, high current density, uniform tip emission, long life, and low noise. The basic structure of the cold cathode field emitter was proposed over 20 years ago by Spindt (1968); however, much of the work since then has centered on improving and developing new cathode structures and their fabrication techniques.

Vacuum-based electronics have a number of interesting features and advantages over solid-state electronics. Vacuum FETs have the potential for high-speed operation; electrons moving through a vacuum do not experience any lattice effects or saturation as do electrons in semiconductors. Cutoff frequencies to 1000 GHz are predicted (Utsumi 1991). Certain temperature effects found in semiconductors, such as increased junction leakage currents or decreased mobility, would not exist in a vacuum FET. High-temperature operation limited only by the process temperatures in fabricating the vacuum FETs could be possible. Vacuum FETs could be relatively immune to degradation by radiation. Radiation effects found in semiconductors, such as lattice or oxide damage, may not affect the vacuum FET as severely as solid state-based electronics. High-temperature and radiation tests need to be carried out to confirm these assumptions. The largest commercial driving force for the development of vacuum microelectronics is for the development of high-resolution flat panel displays based on cold cathode emitters (also called field emitters). The advantages of a field emitter for flat panel display include brightness, efficiency, spatial resolution, gray-scale imaging, and a compact size.

Physical Processes in Vacuum Microelectronics

Field emission is generally defined as the emission of electrons from a solid surface into a vacuum under the influence of high electric fields. The high electric field thins or deforms the vacuum barrier, allowing electrons to tunnel through the barrier. In thermionic emission or photoemission, electrons are emitted over the barrier when given sufficient energy to do so. Experiments involving field emission in which high voltage was applied to pointed metal cathodes began in the late nineteenth century. R. W. Wood (1897) was the first researcher to report work on field emission. Schottky (1923) proposed that field emissions were caused by the complete reduction of the surface barrier potential. Fowler and Nordheim (1928) published the first clear explanation of field emission using quantum theory, explaining that electrons tunnel through the vacuum barrier. However, field emission had no practical applications because of the high voltages required to sustain electron emission; fabrication techniques of the day could not produce emitters small and sharp enough to lower the emission voltage.

The Fowler-Nordheim equation describing field emission current density, J , from a cold cathode is given by:

$$J = 1.54 \times 10^{-6} (E^2/\phi) \exp(-6.83 \times 10^{-7} \phi^{1.5}/E) \quad (1)$$

where ϕ is the emitter material work function and E is the electric field at the emitter surface. From Equation (1), we see that the emission current is exponentially dependent on the emitter work function and the electric field at the emitter surface. Emission currents can be rapidly increased by increasing the electric field or choosing an emitter material with a low work function. The work function has the greater effect on the emission current.

Considerable research effort has focused on improving field emission performance by developing structures which enhance the electric field but decrease applied voltages, and by searching for suitable emitter materials with low work functions. The magnitude of the electric field can be affected in three ways. The electric field will increase as the tip-to-gate spacing is decreased; given identical geometries, the electric field should scale linearly. The tip-to-gate spacing is currently limited by microelectronic fabrication capabilities. As nanofabrication technologies allow the tip-to-gate spacing to be reduced and the field strength to increase, the field magnitude will be limited by the dielectric strength of the insulating materials used to separate the tip from the gate. The voltage applied between the emitter and gate can be increased to increase the electric field, but the voltage should be kept as low as possible to allow the vacuum microelectronics to interface with the solid-state electronics. The shape of the emitter tip can also affect the magnitude of the field strength. Sharpening the tips of field emitters will increase or

enhance the field strength locally and allow higher emitted current. E in Equation (1) can be replaced by $F = \beta E$, where β is the geometrical field enhancement factor and is a function of the radius of curvature at the cathode's emission point. The evaluation of the enhancement factor is difficult but has been estimated to be as high as a few hundred.

Equation (1) dictates that an emitter material with the lowest work function should be chosen. However, the ability of the material to be micromachined using existing fabrication techniques, the compatibility of the emitter material with other materials used in the process sequence, and the temperature and dynamic stability of the emitter material must also be kept in mind. The reaction of the emitter material to its operating environment must also be investigated.

Changes on an atomic scale in the emitter may cause instability in the field emission current. The emitter surface (and gate) can be sputtered by ions generated when unwanted residual gases are bombarded by field electrons and by secondary ions generated when the field electrons bombard device electrodes. The effects of ion bombardment can be reduced by operating in an ultra-high vacuum and by designing the vacuum FET so that the field-emitted electrons do not directly bombard the gate. Sharper tips allow the emitter field to be reduced, which can also reduce the secondary ion yield.

Contamination of the emitter tip and the resulting surface diffusion of the contaminants can induce fluctuations. Impurities that exist in the emitter (such as sulfur, oxygen, carbon, silicon, hydrogen, etc.) can diffuse to the emitter surface if the tip temperature is high enough. The use of chemically inert emitter surfaces which are least susceptible to contamination may help, but these surfaces often have high work functions which require large emitter biasing. Emitters may also be stabilized with a thin layer of a more stable compound; silicon emitters can form a silicide layer. Operation in an ultra-high vacuum can reduce the adsorption of contaminants. A preliminary bakeout may desorb some surface contaminants.

Thermal properties of the field emitter may also cause emission fluctuations. Solid surfaces are not static at high temperatures; the loss of surface edge atoms can cause the surface layer to dissolve. Operation at high current densities can also heat the emitter by Joule heat; the tip can be blunted by the dissolution of the surface edges.

FABRICATION OF VACUUM TRIODES

Cold cathode vacuum microelectronic devices typically consist of a sharp emitter tip or wedge separated from a grid by a micron or less, with an anode at a considerably greater separation. While a great number of fabrication approaches have been developed to produce these devices, none has been identified as being clearly superior. Our approach to the problem of fixing the emitter-to-grid separation relies not on photolithography, but rather on the thickness of a deposited insulating film. We form the sharp wedge emitters using techniques which are commonly employed during fabrication of integrated circuits.

The processing steps used to fabricate the cold cathode vacuum microelectronic devices are shown in Figure 2. First, a vertical step is formed in either deposited or thermally grown oxide using standard reactive ion etching (RIE) techniques. A thin conducting grid is then deposited and patterned. Next, a conformal oxide is deposited to define the emitter-to-gate separation. A conformal conductor is deposited on the emitter-to-gate separation oxide layer. Anisotropic RIE is used to form the emitter wedge from the top layer of conducting film. Finally, the oxide is partially removed by either RIE or wet isotropic etching. Figure 3 shows a cross-section of the emitter wedge before the final removal of the oxide separator. Note that the emitter is separated from the grid by only 0.2 micrometer. All of the processing to date has been on silicon substrates, and some of the processing is carried out at high temperatures (> 720 K).

VACUUM TRIODE TEST RESULTS

Researchers often test to see if their field emitters follow Fowler-Nordheim behavior by plotting a certain form of Equation (1), which can be simplified into the following form:

$$\log(I/V^2) = -\beta/V + \alpha, \quad (2)$$

where I is the emission current, V is the cathode-grid voltage, and α and β are constants.

Equation (2) indicates that a semilogarithmic plot of I/V^2 versus $1/V$ will produce a straight line for Fowler-Nordheim emission. The slope of the line can be used to determine the magnitude of the work function and the geometric enhancement factor that relates E and the applied voltage V . Figure 2 shows a typical Fowler-Nordheim plot. The plots can also be used to show that the emission is temperature independent and rectifying.

We have tested triode devices using the process described above. The triode was fabricated with many emitters in parallel; the separation between emitters was 10 micrometers. Figure 4 shows the current voltage characteristic of one such part in a triode configuration with the anode at 5000 V. The anode is vertically separated from the emitter by 10 mm. The data are replotted Fowler-Nordheim fashion in Figure 5. This device readily and visibly excited a phosphor deposited on the anode.

MODELING OF VACUUM TRIODES

A computer code has been developed to model the performance of the vacuum triode. Particular emphasis is placed on modeling the emitter structure tip size to determine the field enhancement caused by the tip size and shape. Emitter-to-gate separation and geometrical relation are also modeled to determine the electric field at the tip and to predict the current emitted from the tip. Electron trajectories around the emitting tip are calculated and plotted to estimate electron transport to the anode and electron capture by the grid.

A two-dimensional, finite-difference, Poisson solver code was used to calculate the potential between the cathode, grid, and anode using an alternating direction implicit algorithm. The coordinate system used for the finite difference mesh was a $\ln(\text{radius})$ -theta system with the origin being placed at the center of the emitting tip of the wedge. The $\ln(\text{radius})$ coordinate allowed the use of a variably spaced mesh in the r -direction. The mesh size was fine near the anode tip and grid region, allowing more mesh points near the region of most interest with respect to calculating field strengths caused by the emitter shape and interaction with the grid. Figure 6 illustrates the electron trajectories and equipotentials calculated by the finite difference code.

CONCLUSIONS

Cold emission cathode triodes have been fabricated and tested. The electrical characteristics measured included grid voltage, anode voltage, and anode current. From these measurements, Fowler-Nordheim behavior was observed for the emission current.

Acknowledgments

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Figure 1. Schematic of Cold Cathode Triode.

Figure 2. Overview of the Gated Fillet Fabrication Process

Figure 3. Scanning Electron Micrograph of a Cross Section Through a Device Just Prior to the Final Oxide Etch Step.

Figure 4. The Current Measured Between the Emitter and an Anode as a Function of Emitter to Grid Potential.

Figure 5. Fowler-Nordheim Plot of the Data Given Above.

Figure 6. Model of Cold Cathode Triode.

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