INVESTIGATION OF AN NEA DIAMOND VACUUM MICROTRIODE ARRAY

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ABSTRACT

The properties and characteristics of vacuum microtriodes based on NEA diamond surfaces were modelled. Specifically, an NEA diamond vacuum microtriode array was investigated using electrical measurements, electron optics software, and microwave circuit simulation. Data for emission current versus applied voltage for various anode-to-cathode distances for diamond NEA surfaces was analyzed and various parameters were extracted. Electron optics software was used to determine Fowler-Nordheim and space-charge-limited DC I-V characteristics for each microtriode. Microwave circuit simulation was done to determine the behavior of arrays of these vacuum microtriodes in an RF amplifier circuit.

INTRODUCTION

In this work, a set of simulations are presented for diamond NEA emission vacuum microelectronic devices, in which electrons are emitted from a diamond cathode into vacuum and are collected at an anode spaced a few micrometers away. Unlike traditional thermionic vacuum tubes, which require a heated cathode in order to obtain significant current densities, these cathodes would be fabricated by growing a thin film of polycrystalline diamond on silicon and then using appropriate surface treatments to obtain a cold cathode with a negative electron affinity (NEA) surface. Much work has been previously reported concerning current emission from diamond surfaces [1, 2, 3, 4, 5].

Vacuum microtriode structures have been investigated utilizing a molybdenum or silicon cathode shaped in the form of a conic tip. Measurements have been reported for arrays of these types of structures [6, 7, 8]. In the simulations done in this work, the difficulties involved in fabricating these tips is avoided by assuming that the emitting cathode surfaces are flat. The usefulness of these types of flat-emitter vacuum microtriodes in high-frequency RF circuits was recognized by Eastman [9].

We simulated the DC I-V characteristics of the vacuum microtriodes using EGN2, a commercially available electron optics simulation program [10]. First, a set of simulations were done using parameters extracted from recent diamond NEA emission data. It is hoped that, eventually, for NEA diamond surface emission, space-charge-limited current (SCLC) will be obtained (i.e., the electric field at the cathode surface will drop from a large value to approximately zero). In order for the microtriodes examined in this work to operate in the SCLC regime, emitted current denisities must exceed 100 A/cm^2. To investigate the usefulness of these microtriodes for microwave circuits, simulations for these structures assuming SCLC were performed.

From the SCLC results, a large-signal circuit model for a 1×1 mm^2 array of each microtriode was developed. This model was implemented in Microwave Harmonica, a commercially available microwave circuit simulation program [11]. The circuit simulator was used to predict the performance for each microtriode array in a microwave amplifier circuit. The results of these simulations indicate that diamond NEA vacuum microtriodes are promising devices for high-power, high-frequency microwave circuits.

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METHODS

Diamond NEA Emission Data

Typical diamond NEA emission data was taken from our research group and used as a basis for Fowler-Nordheim (F-N) emission simulations. This data indicates that diamond surfaces for which the presence of NEA has been confirmed by photoemission measurements show a F-N dependence of current with anode voltage and cathode-to-anode spacing. That is, the emitted current has the form

$$I = k \left(\frac{\beta V_a}{d} \right)^2 \exp \left(\frac{-6530 d \phi^{3/2}}{\beta V_a} \right) \tag{1}$$

where V_a is the anode voltage (V), d is the anode-to-cathode spacing (μm), ϕ is the barrier height of the NEA surface (eV), β is the field-enhancement factor, and k is a data-fitting parameter (with units of $\mu A \cdot \mu m^2/V^2$).

Specifically, the data used in these simulations was originally reported by Bozeman, et al [12]. This data was obtained from a 3.2-μm-thick chemical vapor deposited (CVD) diamond film grown on silicon. This film had a 1.1×10^{18} cm^{-3} boron concentration (confirmed by SIMS measurements), a (110) texture surface morphology, and a Raman FWHM of 9.4 cm^{-1}. The current was measured by placing a 2-mm-diameter cylindrical platinum anode with a flat end near the diamond film surface (2.6 to 19.8 μm).

Analysis of the data indicated that this film exhibited a threshold electric field of 28±2 V/μm, i.e., 0.1 μA of current were obtained when 28±2 V/μm appeared at the sample surface. With the assumption that $\beta = 1$ (the surface is perfectly flat, so no field enhancement has taken place), it was found that a reasonably good fit to the data could be obtained using $\phi = 0.16 \pm 0.04$ eV and k = 387.1 $\mu A \cdot \mu m^2/V^2$. These values of ϕ, β, and k were used in the subsequent F-N DC I-V simulations.

Device Geometries

A vacuum microtriode structure originally proposed by Eastman [9] is shown in Fig. 1. Electrons are emitted into vacuum by a cathode, pass by 0.3×0.3 μm^2 metal grid electrodes

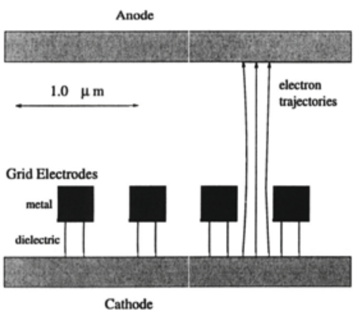


Figure 1: Vacuum microtriode structure proposed by Eastman [9].

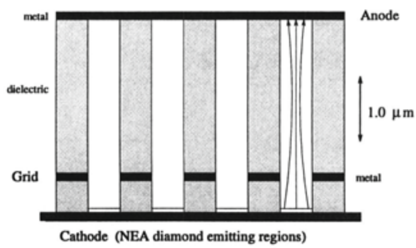


Figure 2: Vacuum microtriode structure proposed by our group.

(which are spaced 0.3 μm apart and sit on 0.15×0.3 μm^2 SiO_2 supports), and proceed on an additional 1.0 μm to an anode.

The electrode geometry of a vacuum microtriode of our own design is shown in Fig. 2. In this structure, electrons are emitted from 0.5-μm-wide flat NEA diamond surfaces, pass by 0.5×0.1 μm grid electrodes (which are spaced 0.5 μm apart and sit on 0.5×0.45 μm^2 SiO_2 supports), and proceed an additional 2.5 μm to the anode (supported by 0.5×2.45 μm^2 SiO_2 supports).

F-N-Type Emission DC I-V Simulations

DC I-V simulations were done for the two microtriode geometries using the EGN2 electron optics simulator [10]. The NEA emission data described above was implemented using the derived parameters β,ϕ, and k to calculate F-N current emission. To maximize the F-N current flowing from cathode to anode, the voltage on the anode should be as large as possible. However, there is a limit to the electric field that can exist in the device; dielectric breakdown and other detrimental effects can occur. For this reason, the maximum electric field allowed in the F-N current simulations was 100 V/μm. This means that no more than $\pm$30 V can be applied to the grid electrodes in the Eastman device, and no more than $\pm$45 V can be applied to the grid electrodes in our proposed structure, when the cathode is grounded.

An example of a F-N emission simulation for the Eastman device is shown in Fig. 3. Note that these device structures can be analyzed in half-space due to their symmetry, and this improves computational efficiency. The Eastman device was biased with 30 V on the control grid and 130 V on the anode. For a 1 $\times$ 1 mm^2 array of triodes, this resulted in

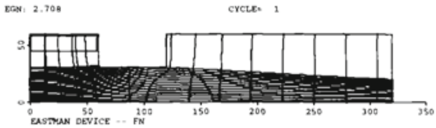


Figure 3: Fowler-Nordheim current emission simulation for Eastman structure.

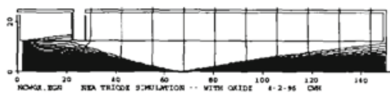


Figure 4: Space-charge-limited current simulation for our proposed structure.

a DC anode current of 1.34 mA and a DC grid current of 0.676 mA. Thus, the DC power dissipation at the anode is 0.174 W and the dissipation at the grid is 20.3 mW. At this bias point, simulation of anode current modulation by grid voltage indicated a transconductance (g_m) of 0.242 mS and an anode resistance (r_a) of 137 kΩ.

For our proposed structure, the microtriode was biased with 45 V on the control grid and 290 V on the anode. For a 1 $\times$ 1 mm^2 array, the DC anode current was 5.48 mA and the DC grid current was 0.514 mA. Thus, the DC power dissipation at the anode is 1.59 W and the disspation at the grid is 23.1 mW. At this bias point, simulation of current modulation indicated a g_m of 0.658 mS and an r_a of 78.1 kΩ.

SCLC DC I-V Simulations

In the SCLC regime, the vacuum microtriode anode current is given by [13]

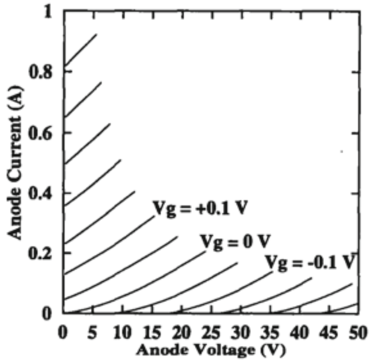
$$I_A = K(V_A + \mu V_G)^{3/2} \tag{2}$$

where K is the perveance (A/V$^{3/2}$) and μ ($= r_a \times g_m$) is the amplification factor. We approximated the grid current by way of the expression

$$I_G = FK\mu^{3/2}(V_A + \mu V_G)^{3/2} \tag{3}$$

where F is determined by device simulations.

For a 1 $\times$ 1 mm^2 array of the Eastman device, simulations yielded an amplification factor (μ) of 171, a perveance (K) of 1.75 mA/V$^{3/2}$, and a grid current constant (F) of 3.09 $\times$ 10^{-4}. An example of a SCLC simulation for our proposed structure is shown in Fig. 4. For a 1 $\times$ 1 mm^2 array, simulations yielded a μ of 56.4, a K of 9.90 mA/V$^{3/2}$, and an F of 2.75 $\times$ 10^{-4}. These simulations lead to an anode current vs. anode voltage and grid voltage characteristics for arrays of the Eastman device and our proposed structure as shown in Figures 5 and 6, respectively.



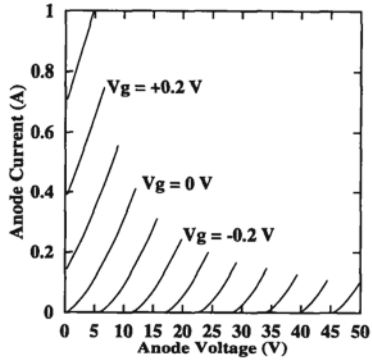


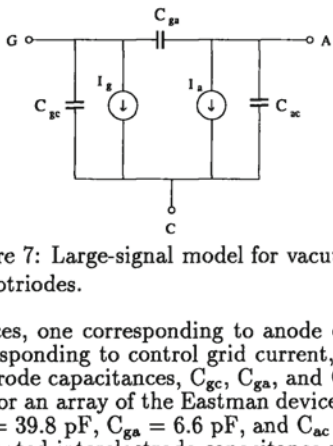
Figure 5: SCLC DC I-V characteristics for Eastman structure array.

Figure 6: SCLC DC I-V characteristics for an array of our proposed structure.

Microwave Circuit Simulations

Microwave circuit simulations were performed using Microwave Harmonica, a commercially available software package. This program is capable of both linear and nonlinear circuit analysis by way of harmonic balance calculations.

To perform an accurate nonlinear simulation of each microtriode array, a large-signal model was developed, as shown in Fig. 7. This large-signal model contains two current



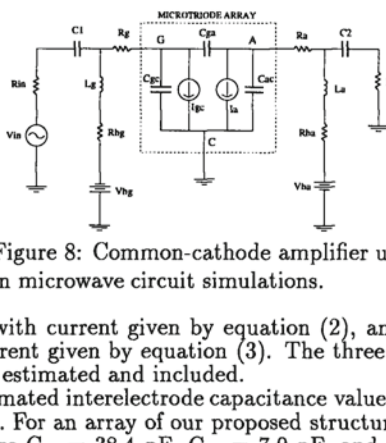


Figure 7: Large-signal model for vacuum microtriodes.

Figure 8: Common-cathode amplifier used in microwave circuit simulations.

sources, one corresponding to anode current, with current given by equation (2), and one corresponding to control grid current, with current given by equation (3). The three interelectrode capacitances, C_{gc}, C_{ga}, and C_{ac}, were estimated and included.

For an array of the Eastman device, the estimated interelectrode capacitance values were $C_{gc} = 39.8$ pF, $C_{ga} = 6.6$ pF, and $C_{ac} = 2.8$ pF. For an array of our proposed structure, the estimated interelectrode capacitance values were $C_{gc} = 38.4$ pF, $C_{ga} = 7.0$ pF, and $C_{ac} = 1.5$ pF.

An array of each type of microtriode was simulated in a common-cathode amplifier circuit, as shown in Fig. 8, in order to determine each array's usefulness as an amplifier component for frequencies rnging from 10 MHz up to 10 GHz. The simulation assumed low-resistance DC and RF voltage sources and low-resistance array package leads. The load resistance was set equal to the anode resistance of the array at the quiescent point [14].

For the Eastman array circuit simulation, a load of 70 Ω was used. The array was biased with 19.2 V on the anode and 0.0547 V on the grid. A 0.15-V magnitude RF input signal was used. As shown in Fig. 9, this array delivered about 1.1 W of power to the load at low

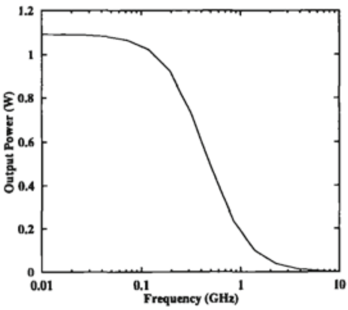


Figure 9: Eastman array output power vs. frequency with a 70-Ω load.

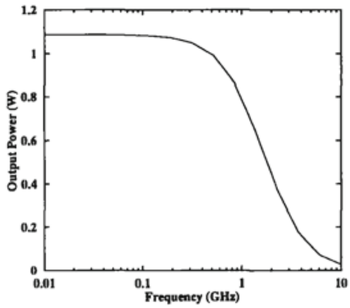


Figure 10: Output power for our proposed array vs. frequency with a 24-Ω load.

frequency and about 0.2 W of power at 1 GHz.

For our proposed device array circuit simulation, a load of 24 Ω was used. The array was biased with 11.0 V on the anode and 0.0345 V on the grid. A 0.23-V magnitude RF input signal was used. As shown in Fig. 10, the array delivered about 1.1 W of power to the load at low frequency and about 0.8 W of power at 1 GHz.

RESULTS AND DISCUSSION

The results obtained for the F-N emission simulations in this work show what type of vacuum microtriode device performance could be expected using typical NEA diamond cold cathodes as they exist today. Obviously, these devices require large anode voltages (130 to 290 V) and suffer from small anode currents (1 to 6 mA), small transconductances (0.2 to 0.7 mS) and large grid leakage currents (0.5 to 0.7 mA). Obviously, these are not practical devices for high-power, high-frequency microwave applications.

When the SCLC DC I-V characteristics for the Eastman device and our proposed structure are compared, it is seen that although Eastman's structure has an amplification factor three times as high (i.e., the grid voltage exerts more control over the grid current), the perveance for our structure is more than five times higher. It should be noted that some of the electron trajectories in the simulations of our proposed device entered and passed through the dielectric layers, indicating that dielectric charging of the SiO_2 surface may need to be taken into account in future simulations.

The microwave circuit simulations reveal that both microtriode geometries suffer from the Miller effect. That is, the capacitance between the grid and the anode is a feedback capacitor, and circuit analysis for these triodes shows that the total capacitance which appears at the grid input is the sum of the grid-to-cathode capacitance plus the grid-to-anode capacitance times the voltage gain of the array [15]. This phenomenon severely reduces gain at higher frequencies. To overcome this problem, a screen grid electrode could be included in the device design, inserted between the control grid and the anode. This would essentially eliminate the control-grid-to-anode capacitance and increase the output power at higher frequencies.

This work has shown the feasibility of using NEA diamond vacuum microtriodes for microwave circuits, but the device geometry and circuit design presented are not optimized for any particular application. Additional work needs to be done to determine optimal designs for these vacuum microtriodes and circuits containing them for particular microwave circuit applications, such as cellular phone or radar subsystems.

CONCLUSIONS

In this work, typical diamond NEA emission data was used to predict the performance of two different vacuum microtriode arrays. It was concluded that with currently attainable current emission densities, useful devices for high-power and high-frequency RF circuits are not attainable. Simulations were then done for the vacuum microtriode structures assuming that emission from the NEA diamond surface would allow the devices to operate in the space-charge-limited regime. These device and circuit simulations indicate that these vacuum microtriode structures operating in the SCLC regime have potential for use in high-power and high-frequency microwave circuits.

ACKNOWLEDGMENTS

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