THz generation in a DC diode with base resistor

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***Abstract*—We have recently discovered a novel mechanism for generating oscillating current at THz frequency in a DC vacuum microdiode with a series resistor. We performed simulations of field emission in a planar microdiode with an appreciable resistor and observed the emergence of regular oscillations in the diode current due to loading of the resistor modulating the surface electric field and subsequently the emission [1]. Here we extend our previous work to examine how field enhancement at the cathode surface affects the operating parameters. It is shown that using field emitter arrays the voltage can be reduced significantly while maintaining a robust diode current oscillating in the THz frequency range. Using molecular dynamics simulations, we show how the configuration of the field emitter array, in the context of other diode parameters, affects the performance of the oscillator.**

***Index Terms*—Diodes, vacuum electronics, terahertz sources, beam loading, simulations**

I. Introduction

A great number of modern vacuum electronic devices rely on electron field emission. A characteristic of this emission mechanism is its exceptionally strong dependence on the electric field at the point of emission. This makes it very suitable for control by use of applied electric fields. Another benefit is that by making use of local field enhancement, e.g. on a microscopic tip, it is possible to draw current with moderate applied voltage.

We have previously demonstrated that it is possible to use the great sensitivity of field emission to field strength to modulate the current in a diode in such a way that persistent and regular oscillations in the diode current appear. The method for doing this is to apply a sufficiently large base resistor to the cathode, in series with the voltage source, whereby current drawn from the cathode will load the resistor and subsequently decrease the diode voltage. As the diode potential drops, so does the electric field at the cathode and, as a result, the rate of emission from it. The emission will not increase again until the electrons traversing the diode gap have left it and ceased to induce current in the resistor. Under favorable conditions this becomes a sustainable periodic process. Importantly, the resistor must be of such magnitude that the potential drop across it is of the same order as the applied potential.

Our prior work was primarily done looking at planar diodes, where the applied potential is on the order of thousands of Volts and the gap spacing around one micrometer. For a practical device this potential is unsuitably high. However, by making use of field enhancement it may be possible to extract considerable modulated current with a reasonable applied potential. In this paper we show that it is possible to excite persistent oscillatory current when the electron source is a field emitter array.

II. Simulation Model and Method

The system under consideration is an infinite planar diode with the cathode in the x–y plane at $z = 0$ and the anode at $z = D$. An external voltage source of magnitude V_0 is connected in series to a resistor of magnitude R, across the diode gap. A square patch, of side length L, is embedded in the cathode area. Within it the work function is ω, and without it no emission takes place. Within the patch is a regular $N \times N$ array of field emitters with a fixed pitch, and a field enhancement factor assigned to each emitter.

To calculate electron emission and propagation we use the molecular dynamics code RUMDEED [2]. The code has a self-consistent field emission module that takes into account the local surface electric field due to the applied field, field enhancement, and electric field due to individual electrons and their image partners. It calculates the force on individual electrons using grid-free direct Coulomb interaction between all electrons and image charges in addition to the applied field $\mathbf{E}_0$. Finally, the induced current in the anode (and resistor) is calculated using the Ramo–Shockley theorem [3], $I = \sum_{k=1}^{N_e} q v_k D^{-1}$, where v_k is the velocity of the k-th electron, q is the fundamental charge and N_e is the number of electrons in the gap.

When modeling the field enhancement in the emitter array we begin by calculating the surface electric field for a planar cathode (including discrete space-charge effects), $E_s(\mathbf{r})$, and then multiply it by an enhancement function

$$\beta(\mathbf{r}) = \max\left(\sum_{p=1}^{N} (\beta_p) \exp \frac{-(\mathbf{r}_p - \mathbf{r})^2}{2\sigma_p^2}, 1\right) \quad (1)$$

where $\mathbf{r}_p$ denotes the location of the p-th emitter which has a maximum enhancement factor β_p and lateral extent characterized by σ_p. The enhanced field, βE_s, is then used to calculate local field emission.

However, when calculating forces on individual electrons we neglect the effect of field enhancement and simply assume the applied field acting on a single electron to be $\mathbf{E}_0 = \left(RI - V_0 D^{-1}\right)\hat{\mathbf{z}}$.

The simulation is grid free and includes exact Coulomb interaction between all electrons in the gap and all of the associated image charges. It is fully three dimensional and electrostatic. The time-step is 0.1 fs. Electrons are removed from the simulation when they cross the anode or cathode.

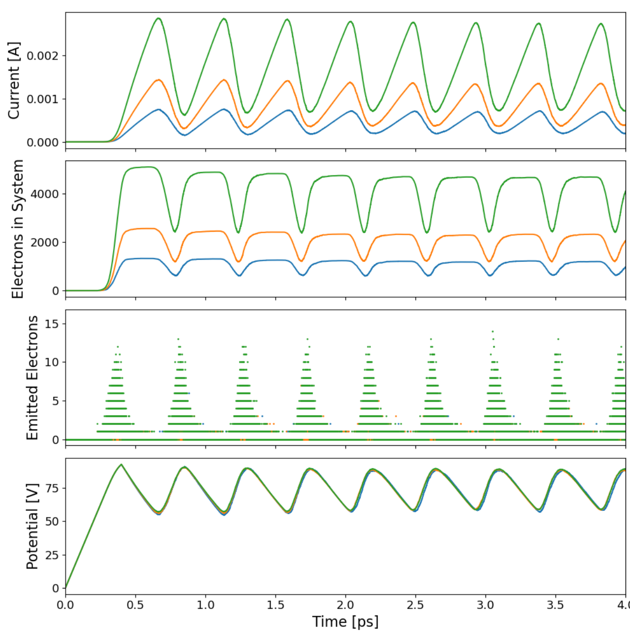

Fig. 1. Anode current, number of electrons in gap, number of electrons emitted, and anode potential as functions of time. Blue: $L = 1000$ nm, $N = 75$, $R = 60$ kΩ. Orange: $L = 1400$ nm, $N = 105$, $R = 30.6$ kΩ. Green: $L = 2000$ nm, $N = 150$, $R = 15$ kΩ. The applied potential is 100 V and work function is 2 eV in all cases.

III. Results and Discussion

We examine a system where the applied potential is ramped up from zero to 100 V. The field emitters have uniform values of field enhancement, $\beta_p = 20$, and extent, $\sigma_p = 3$ nm. The gap spacing is $D = 1000$ nm and the work function is $\omega = 2$ eV. We consider three configurations of side length L, with $N \times N$ emitters and base resistance R. Fig. 1 shows the anode current, number of electrons in the gap, number of electrons emitted, and anode potential as a function of time for the three configurations. It is apparent that it is possible to generate persistent oscillations from a field emitter array. Furthermore, we see that it is possible to maintain the frequency and anode potential while changing the current by appropriately varying the emitter size and base resistor.

In Fig. 2 we show the results when the field enhancement of the tips is varied with a Gaussian distribution of mean, $\overline{\beta_p} = 20$, and standard deviation, $\sigma_\beta = 2$ (not to be confused with the lateral extent of $\sigma_p = 3$ nm). From this we see that uniformity of field enhancement is not a necessary condition of producing persistent oscillations.

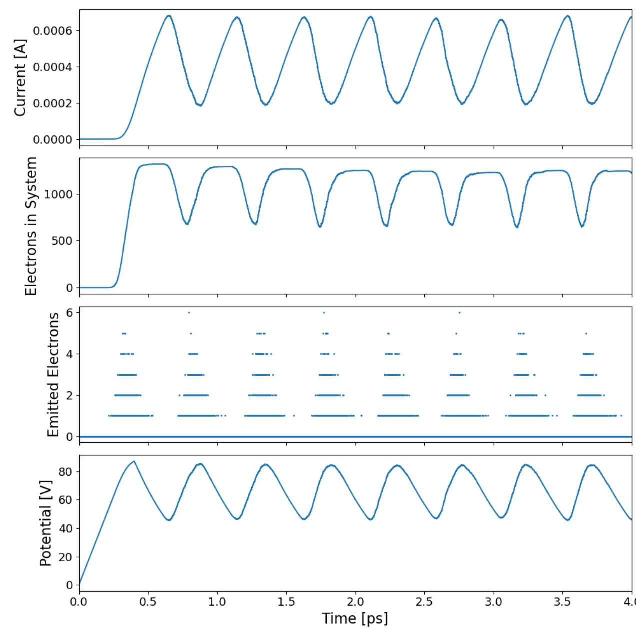

Fig. 2. Anode current, number of electrons in gap, number of electrons emitted, and anode potential as functions of time. $L = 1000$ nm, $N = 75$, $R = 80$ kΩ. Field enhancement is assigned via a Gaussian distribution with average value, $\overline{\beta_p} = 20$ and standard deviation, $\sigma_\beta = 2$. Applied potential is 100 V.

In summary, we have established the existence of controllable current oscillations in a DC diode with a field emitter array on the cathode and a resistive load in series with the power source. A more detailed presentation is forthcoming.

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