Theoretical Analysis of a Geis-Spindt Cold Cathode Diamond Emitter

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Abstract. A quantitative theory for the operation of a Spindt-type cold cathode emitter embedded in a thin diamond film doped with substitutional Nitrogen is presented. The device, recently developed by M. W. Geis and colleagues at the MIT Lincoln Laboratory, is characterized by high field emission currents at low power. The theoretical model treats injection, by internal field emission, at the metal-diamond interface, transport through the diamond film and emission at the diamond-vacuum surface. The calculated I-V characteristics agree well with the experimental results of Geis et al.

1. Introduction

The properties of diamond as a material of choice for cold cathode emitters has been recognized for a while [1]. Recently, Geis et al. [2] (hereafter referred to as GTL) obtained low power levels (threshold below 8 V) for the electron emission of the diamond-based field emitting device with a roughened metal cathode. However, diamond has a wide band gap (5.5 eV) and achieving a significant density of conduction band electrons has been a challenging problem because of the difficulties associated with *n*-doping of the material [3]. To obtain field emission, GTL fabricated a Schottky barrier between the metal and Nitrogen (N) substitutionally doped diamond. The presence of a large concentration (in excess of 10^{19} cm^{-3}) of N bends the energy barrier upwards in the vicinity of the interface making electron transport into the conduction band possible by tunneling. In Fig. 1, we exhibit, according to GTL, a schematic of the whole device with potential curves inside the diamond film. Specifically, there is a sharp drop of the potential near the surface of the metal because of the Schottky barrier that is formed at the interface. Note also the Spindt-type metallic emitter, essential to the operation, which is discussed in the next paragraph.

Field emission can be further enhanced despite the high dielectric constant of diamond ($\epsilon_s = 5.7$), which reduces the field in the vicinity of the metal surface. To concentrate the field around the electron-injecting metallic surface, GTL roughened the surface of the metal by special treatment. This procedure created asperities on the metal which protrude into the diamond film. The resulting concentration of the field lines around the tip enhances further the internal tunneling from the metal into the conduction band of diamond by barrier reduction and thinning. Once an electron is in the conduction band and has traversed the width of the diamond film, it can "slip" into vacuum through negative electron affinity (NEA) surfaces of the diamond crystal without further acceleration by the field [1,2]. Quasi-ballistic electron transport through thin diamond films has been proposed by the authors in previous publications [4] suggesting that the injection current (and its energy distribution) can be sustained during transport to the surface.

2. Internal Field Emission Model

Following Ref. 2 we describe protrusions on the metal tips as spheres of a given radius R . Because of the strong dependence of the current on the field we can consider that the emission starts from the sharpest tips, i.e. those with the highest curvature. Emission from protrusions with lower curvature will not be significant. As a consequence of strong dependence of the tunneling on the geometry of the field (i.e., $\sim \text{Exp}\{-\text{const}/F(R)\}$), we approximated the size distribution of tips' curvature by a delta function. We propose the following model for the operation of this Geis-Spindt device (hereafter called a GEISHE device). (i) Internal field emission through the Schottky barrier is governed by a *Fowler-Nordheim (FN) type equation*. The drop in potential in the depletion layer is nearly equal to the reverse bias (V_B) of the

whole device, so that the electrons injected into the conduction band propagate under essentially zero-field conditions (See Fig. 1). (ii) In formulating this hypothesis, we assume quasi-ballistic propagation of conduction band electrons in thin diamond films, a result based on Monte Carlo simulations by the authors [4]. (iii) NEA of diamond's (111) surface or any other NEA surface allows the electrons in the conduction band to escape into vacuum. It is important to note that the field emission characteristics of the device as a whole are determined primarily by the internal field emission through the Schottky barrier at the metal-diamond interface.

The effect of strong N-doping ($\sim 10^{19}$ - 10^{20} cm $^{-3}$) is twofold. The N ions in the depletion layer create a space charge region near the metal, which concentrates the field, producing a sharp drop in the local potential. With the dopant present, the field near the emitter surface obeys the approximate expression $F \approx V_B/R$; without the dopant the field would, in general, be much smaller and of the order of $F \approx V_B/\epsilon_s d$, where d is the thickness of the diamond film. Secondly, the depletion layer is thin enough to facilitate field-emission transport through the Schottky barrier. For low concentrations of dopant the width of the Schottky barrier increases as $\sim N_d^{-1/3}$ and the tunneling through the resulting thick barrier is much reduced.

The tunneling current through the curved metal-diamond interface can be described by a FN type equation [5]. We consider the image correction for the curved geometry of the tip equal to its flat-surface limit with image force term $1/\epsilon_s$ times weaker for injection into diamond than into vacuum [6].

Our calculated I-V characteristics for a fixed concentration of dopant contains two parameters. These are R , the effective radius of curvature for the tip(s) and, secondly, effective number of tips per unit area. To estimate the radius we match GTL I-V characteristics which is a straight line when plotted in FN coordinates to the theoretical I-V curve. Fitting of our theoretical junction-transport value of the current with experimental values determines both parameters. The slope of the experimental FN curve provides a value for R . Similar matching of the intercept on the ordinate axis for the experimental and theoretical curves yields the density of emitters per unit area.

Figure 1: Schematic diagram of a GEISHE device consisting of a Spindt-type metallic tip embedded in a N-doped diamond film. The potential barrier is illustrated in the diamond outside the depletion layer for nearly zero field conditions. The quantity eV_B is the energy difference between the top of the Schottky barrier and the bottom of the conduction band.

3. Results and Conclusions

The calculated I-V characteristics of the GEISHE are compared with experimental results in Fig. 2. Their near-coincidence should not be surprising, since both curves are straight lines in FN coordinates and one can always match two straight lines by two parameters, which in this case are R and the density of emitters. The essential fact is that the average radius of curvature extracted from our theoretical fit to the experimental I-V characteristics is close to its experimental value. In fact, the near-exponential dependence of the tunneling current on the average radius of curvature provides a sensitive test of the model. We determined this radius as $R=8.2$ nm, which is in good agreement with an average GTL experimental value of about 10 nm.

The effective density of tip emitters per unit area is found from the calculated ratio of tunneling current density obtained from the FN type equation to the experimental current density and has the value of $16,000 \text{ cm}^{-2}$. We shall discuss this number below.

The radius of curvature R deduced from our theoretical analysis is in good agreement with the GTL data on roughness of their surface [2]. By this we mean identification of the "roughness" observed by electron microscopy [1,2], with the average curvature of the "spikes".

The average density of emitting spikes is harder to evaluate. We can roughly estimate the density of the emitting cones from the electron micrograph provided in GTL. This is $\sim 2.3 \times 10^6 \text{ cm}^{-2}$ which is in good agreement with the estimated average distance between cones, $\sim 6-7 \mu\text{m}$. If we again assume that tunneling occurs from the *sharpest protrusion* per emitter, then there is a discrepancy by a factor of 150 between our value deduced from the comparison of the calculated FN curve to the experimental results. An order of magnitude difference can be explained by the fact that only a small fraction of the surface area of the tip participates in emission. The experimental and theoretical results provided in Ref. 7 suggest that a solid angle encompassing only 10-20 degrees on top of the tip effectively contributes to the field emission. We provide below a possible explanation of the remaining discrepancy.

Previously we assumed that every electron in the conduction band eventually escapes into the vacuum. However, GTL samples were made of polycrystalline diamond and not all of the surfaces were (111) with NEA. Because the electrons in the conduction band of diamond is essentially under zero-field conditions, they cannot overcome the potential barrier at the positive electron affinity (PEA) boundary surfaces between grains. Only a fraction of emitters, namely those with a continuous path between the metallic tip and a NEA surface of a diamond crystal thus contribute to the emission. This situation is relatively insensitive to the value of the field above the emission threshold because most of the drop in the potential occurs in the depletion layer even for relatively high fields. This hypothesis acquires additional credence by observation in [8] that an additional field $0 < F < 1 \text{ V}/\mu\text{m}$ is needed to overcome the field from any built-in surfaces with PEA. Irregular values of this field are typical for dynamical properties of disordered media and suggest that the effects of electron zero-field percolation may be responsible for reducing the number of effective emitters.

Figure 2: Emitted current as a function of gate voltage calculated using the modified Fowler-Nordheim type equation. The squares are the data points of Geis et al. [2]. The height of the Schottky barrier at the metal-diamond surface is taken as $\phi_{B0} = 1.9 \text{ eV}$ (compare with Ref. 10).

The latter consideration, suggests that there is the possibility for improved performance of the GEISHE by eliminating the PEA surfaces. This is, perhaps, feasible because their number and orientation are highly dependent on material preparation.

In summary, our treatment of GEISHE has, as its core, three physical assumptions:

- 1) We apply a *Fowler-Nordheim type equation* to the tunneling through the Schottky barrier at the metal-diamond interface.
- 2) We assume *quasi-ballistic propagation in diamond* so that every electron supplied from the metal into the conduction band of the diamond film is presumed to be emitted into vacuum. Current transport through the interface is thus equated with the I-V characteristic of the whole device.
- 3) We consider *near zero-field conditions in diamond outside of the depletion layer*, so that little or no acceleration of electrons occurs on its path to the surface. Once in the conduction band, the charge carriers simply "slip" out of diamond because of the NEA of the emission surface.

Finally, we note that more recently Okano et al. [9] have reported much lower threshold voltages and saturation effects for diamond films deposited on Si substrates. In this case, Okano et al. [9] claim that the saturation effects in field emission are due to space-charge. In contrast to the Ni-diamond interface in the GTL device, the operation of this device involves field transport through a Si-diamond interface and requires a different model and analysis. Such work is in progress.

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