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</thead>
<tbody>
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S. Sun and L. K. Ang

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Analysis of field-emission from a diamond-metal-vacuum triple junction

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A quantitative electron tunneling model is constructed to calculate the electron emission from a diamond-metal-vacuum triple junction, including the effects of the field enhancement at the interface of the triple junction, the reduction on the barrier height and the negative electron affinity on the diamond surface. The difference between the emission processes with and without light exposure is also investigated. © 2012 American Institute of Physics.

Diamond is known to have excellent field emission properties as compared to other semiconductors.¹ The negative electron affinity (NEA) characteristic²,³ on the diamond surface has motivated people to investigate its field emission properties for electron to tunnel from diamond into vacuum. However, with a large band gap (5.5 eV), it is almost impossible to directly get a low turn on voltage for intrinsic diamond. Nevertheless, no n-type dopant suitable for cold field emission has been reported. The best choice is the substitutional nitrogen doped type Ib diamond, with nitrogen forming a deep donor level at about 1.7 eV below the conduction band.⁴ Excellent low-voltage-high-current properties for electron to tunnel from diamond into vacuum. build-in potential at the junction is $V_B = V_a + V_b$, where $V_a$ is the external applied bias and $V_b$ is the potential difference between the peak of the Schottky barrier and the bottom of the conduction band at $V_a = 0$. Note the definition of $V_a$ and $V_b$ can be found in Ref. 14. At the diamond-vacuum interface, the vacuum energy $E_{vac}$ should be below the conduction band $E_c$ to represent the NEA characteristic, and the potential drop is determined by the surface treatment techniques used in the experiment.

Compared to the traditional diamond emitter [Fig. 1(a)], there are three major differences in the triple junction structure [Fig. 1(b)], with its corresponding band diagram depicted in Fig. 1(c) (red curve). First, in addition to the geometrical field enhancement on the metal-diamond interface due to any protrusions on the metal substrate, the local electric field at the metal-diamond-vacuum junction can be further increased by an additional factor, which is up to a value equal to the dielectric constant ($\varepsilon_c = 5.68$) of the diamond.⁵,⁶,⁷ Second, the electrons will transport into the diamond surface states at energy $E_f$, which is found to be 1 eV below the conduction band energy $E_c$ given by $E_c - E_f = 0.7$ eV.⁸ These electrons will face a lower barrier height $\Phi_{B1} < \Phi_B$, which could be as little as 1 eV or up to the metal work function $\Phi_B$ minus the diamond surface binding energy (0.42 eV).⁹ Finally, besides the Schottky barrier $V_1(r)$ at the depletion region, there might be another barrier $V_2(r)$ formed at the diamond-vacuum interface (NEA surface) as long as $E_c > E_{vac} > E_s$.

To calculate the emission current density $J$, we solve

$$J = \frac{m_0q}{2\pi^2\hbar^3}k_BT\int_0^\infty T_c(E) \cdot \ln \left(1 + \exp \left(\frac{E - E_f}{k_BT} \right) \right) \cdot dE,$$

where $m_0$ is the free electron mass, $\hbar$ is the reduced Plank constant, $k_B$ is the Boltzmann constant, $T$ is the temperature, and $T_c(E)$ is the corresponding electron tunneling coefficient through either a single barrier [$V_1(r)$] or a dual-barrier [$V_1(r)$ and $V_2(r)$] (see red curve in Fig. 1(c)). Note an earlier work,¹⁴ which directly used the Fowler-Nordheim (FN) law¹⁵ to calculate the emission current is not accurate as the potential barrier $V_1(r)$ [see Eq. (2) below] is very different from the specific potential form $V(r) = \Phi_B1 - F \times r - Q/r$ assumed in the FN law, where $Q/r$ is the image charge potential.

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The expression of $V_1(r)$ can be derived based on prior models by considering the metal protrusive surface as spheres with radius $R$.\textsuperscript{14,19,20} which give analytical expressions of

\begin{equation}
V_1(r) = C_1 - \frac{C_2}{r} - \frac{2\pi qN_d r^2}{3\epsilon_r \epsilon_0}, \quad (2)
\end{equation}

\begin{equation}
C_1 = -\Phi_{B1} + \frac{2\pi qN_d R^2}{3\epsilon_r \epsilon_0} + \frac{4\pi qN_d (R + \omega)^3}{3\epsilon_r \epsilon_0 R}, \quad (3)
\end{equation}

\begin{equation}
C_2 = \frac{4\pi qN_d (R + \omega)^3}{3\epsilon_r \epsilon_0}. \quad (4)
\end{equation}

Here, $\epsilon_r = 5.68$ is the dielectric constant of diamond, $\epsilon_0$ is the vacuum permittivity, $qN_d$ is the charge density within the depletion layer of width $\omega$, $N_d$ is the donor density, and $\Phi_{B1}$ is the barrier height at the metal-diamond interface. By assuming a flat band structure far away from the barrier, we have $V_1(R + \omega) = V_B - \Phi_{B1}$, which can be substituted into Eq. (2) to obtain the build-in potential $V_B$

\begin{equation}
V_B = \frac{4\pi qN_d \omega^3}{3\epsilon_r \epsilon_0 R} + \frac{2\pi qN_d \omega^2}{\epsilon_r \epsilon_0}. \quad (5)
\end{equation}

This equation can be used to determine the depletion width $\omega$ as a function of build-in potential $V_B$ for fixed $N_d$ and $R$. For the second barrier $V_2(r)$ at the diamond-vacuum interface, it is assumed to be $V_2(r) = \Phi_{B2} - V_a - F \times r$, where $\Phi_{B2} = E_{vac} - E_f$ is the barrier height, $F = qV_a/D$ is the average electric field, $V_a$ is the external applied voltage, and $D (=100 \text{ nm})$ is the diamond slab’s thickness.\textsuperscript{6}

Figure 2 demonstrates, respectively, the Schottky barrier profile $V_1(r)$ for (a) various build-in potential $V_B$ at $N_d = 10^{19} \text{ cm}^{-3}$ and $R = 10 \text{ nm}$, (b) various donor concentration $N_d$ at $V_B = 10 \text{ eV}$ and $R = 10 \text{ nm}$, and (c) various metal sharpness $R$ at $V_B = 10 \text{ eV}$ and $N_d = 10^{19} \text{ cm}^{-3}$. The other parameters are $\Phi_{B1} = 3 \text{ eV} < \Phi_{B2} = 4 \text{ eV}, V_{B1} = \Phi_{B1} - (E_f - E_v) = 2.3 \text{ eV}$ and the metal fermi energy is kept at $E_f = 10 \text{ eV}$. For all the figures, metal fermi energy (dashed line) is set at $E_f = 6 \text{ eV}$.
6 eV. By increasing $V_B$ from 8 to 12 eV, which is equivalent to an applied voltage of $V_a(=V_B - V_b) = 5.7$ to 9.7 eV, the barrier width will become smaller, as shown in Fig. 2(a). The depletion width $\delta$ decreases with larger $N_d$, and increases with larger $R$, as shown in Figs. 2(b) and 2(c), respectively.

To compare our model with experimental results, we have used $R = 10$ nm, and the donor concentration $N_d = 10^{19}$ cm$^{-3}$ in order to pin the deep donor level $E_F$ at 1.7 eV below $E_C$ according to experimental condition. In doing so, we calculate the emission current using Eq. (1) as a function of applied external voltage $U_b$, which is decreased with larger $\delta$, and increases with larger $R$, as shown in Figs. 2(b) and 2(c), respectively.

First, without including the additional field enhancement at the triple junction between metal, diamond, and vacuum, we consider only the reduction of the Schottky barrier height ($\Phi_B = 3.5$ eV), and the existence of the second barrier ($\Phi_B = 1$ eV) as shown in Fig. 3(a) (dashed lines), which shows that the emission current density $J$ is about $10^{-4}$ A/m$^2$ at around $V_a = 5.3$ V, much smaller as compared to the conventional diamond emitter operating around 8 to 10 V with a barrier $\Phi_B \approx 4$ eV. This finding proves that a smaller Schottky barrier $\Phi_B$ do contribute to a smaller turn-on voltage; however, the calculated value $V_a = 5.3$ V (or electric field $F = 5.3$ V/100 nm = 53 V/μm) is still significantly larger as compared to 0.6 V (or $F = 6$ V/μm) reported in the triple junction experiment.

Thus, it is rational to include the additional field enhancement factor due to triple junction, which is up to $e_\tau = 5.68$. By assuming an enhancement of 5, the calculated results are shown in Fig. 3(a) [solid lines] at $\Phi_B = 2.25$, and 3.5 eV (left to right), where $V_a$ is decreased by a factor of 5, closer to 0.6 V. For example, we have $V_a = 1.06$ V and 0.68 V, respectively, at $\Phi_B = 3.5$ eV and 2.5 eV. The emission current density is independent on the second barrier height $\Phi_B$, where the results are nearly identical for $\Phi_B = 1$ eV and $\Phi_B = 0.5$ eV. Hence, we conclude that the effects of field enhancement at the triple junction and the reduced Schottky barrier height $\Phi_B$ are essential to get a smaller turn-on voltage to explain the experimental findings.

Lastly, we will briefly investigate the emission process with and without light exposure reported in the experiment. When the cathode is exposed to light with photon energy higher than 2 eV (the ionization energy of nitrogen), the photon-generated electrons will neutralize the nitrogen dopant, which results in a larger turn on voltage due to the reduction on the donor concentration. However, as the applied voltage increases, the dopant will be re-ionized recovering to the emission-in-darkness characteristic at $V_a$ $\approx$ 3 V. Since the exact relationship between the increment rate of the donor concentration $N_d$ and the applied voltage $V_a$ is unknown, we simply assume a linear relation governed by $N_d = 10^{19} \times (V_a/3)$ cm$^{-3}$ for $V_a < 3$ V, and $N_d = 10^{19}$ cm$^{-3}$ for $V_a \geq 3$ V in our calculation. The results are shown in Fig. 3(b), which show the difference between the emission in the darkness (solid line) and the emission in the light (dash line) at $\Phi_B = 2.5$ eV. The turn-on voltage increases to 1.25 V with light exposure, which is quite comparable with the experimental data of 1.6 V.

![FIG. 3. (a) The emission current density with (solid lines) and without (dashed line) the additional field enhancement (=5) at the triple junction with different $\Phi_B$ and fixed $\Phi_B = 1$ eV. For solid lines, $\Phi_B = 2.25$, and 3.5 eV (left to right). For dashed line, $\Phi_B = 3.5$ eV (b) The emission current density with (dashed line) and without (solid line) light exposure at $\Phi_B = 2.5$ eV and $\Phi_B = 1$ eV.](image)

Our work may be extended to other triple-junction based structures or novel materials, such as graphene which has different field emission property.

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