Theoretical study of field emission from dielectric coated surfaces

Peng Zhang, Yang Zhou, and Yi Luo

Department of Electrical and Computer Engineering
Michigan State University, East Lansing, MI, 48824 USA
Email: pz@egr.msu.edu

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Introduction

• Electron field emission plays an essential role in a wide range of applications, including
  – Electron microscopes
  – X-ray sources
  – High current cathodes
  – High power electromagnetic sources and amplifiers
  – Vacuum microelectronics
  – Emerging quantum nanoelectronics

• Field emitters attract intensive attention, because of
  – High efficiency
  – High brightness
  – Low emittance
  – Miniaturized device size
Field emitters with coating

• **Artificial coating**: Ultra-thin coatings are fabricated onto metallic cathodes to provide chemical and mechanical protection, and longer current stability, smaller turn-on electric field and enhanced current emission due to the lowering of the effective potential barrier [1], [2].

• **Naturally formed coating**: Native oxides or foreign adsorbates can be easily formed on the surface of the emitter at low vacuum condition [3].

• Coating on the cathode surface forms a double-layer potential barrier
  – Strongly influences the field emission current.
  – Has its potential to change the electrons’ mean transverse energy behavior that affects beam quality, important to photoinjectors for future x-ray free electron lasers (XFELs) [4]

Exact Solution to Schrödinger Equation

\[ -\frac{\hbar^2}{2m} \frac{\partial^2 \psi(x)}{\partial x^2} + [V(x) - \varepsilon] \psi(x) = 0 \]

\[ \psi(x) : \text{complex electron wave function} \]

Potential barrier

\[ V(x) = \begin{cases} 
0, & x < 0, \\
E_F + W - \chi - eF_{\text{die}}x, & 0 \leq x < d, \\
E_F + W + e(F - F_{\text{die}})d - eFx, & x \geq d.
\end{cases} \]

Exact Solution to Schrödinger Equation

\( x < 0 \) (Inside metal)

\[
\psi_I(x) = e^{i k_0 x} + R_1 e^{-i k_0 x}
\]

Incident plane wave \hspace{1cm} Reflected waves

\( k_0 = \sqrt{2m\varepsilon/\hbar^2} \)

\( 0 \leq x < d \) (Inside dielectric)

\[
\psi_{II}(x) = aAi(-\eta_1) + bBi(-\eta_1)
\]

\( x \geq d \) (Vacuum Region)

\[
\psi_{III}(x) = T_3[Ai(-\eta_2) - iBi(-\eta_2)]
\]

\[
\eta_1 = \left(\frac{2m\varepsilon_{\text{diel}}}{\hbar^2}\right)^{1/3} \left(x + \frac{\varepsilon - V_1}{e F_{\text{diel}}}\right)
\]

\[
V_1 = W + E_F - \chi
\]

\[
\eta_2 = \left(\frac{2m\varepsilon}{\hbar^2}\right)^{1/3} \left(x + \frac{\varepsilon - V_2}{e F}\right)
\]

\[
V_2 = W + E_F + e(F - F_{\text{diel}})d
\]
Exact Solution to Schrödinger Equation

Boundary conditions at metal-dielectric interface & dielectric-vacuum interface

\[ \psi_I(x = 0) = \psi_{II}(x = 0) \]
\[ \frac{\partial \psi_I}{\partial x} \bigg|_{x=0} = \frac{\partial \psi_{II}}{\partial x} \bigg|_{x=0} \]
\[ \psi_{II}(x = d) = \psi_{III}(x = d) \]
\[ \frac{\partial \psi_{II}}{\partial x} \bigg|_{x=d} = \frac{\partial \psi_{III}}{\partial x} \bigg|_{x=d} \]

\[ \overset{\rightarrow}{R}_1, a, b, & T_3 \]

Electron transmission probability

\[ D(\varepsilon) = \frac{J_3(\varepsilon)}{J_i(\varepsilon)} \quad \text{with} \quad J = \frac{i\hbar}{2m} (\psi \nabla \psi^* - \psi^* \nabla \psi) \]
Exact Solution to Schrödinger Equation

Electron transmission probability

\[ D(\varepsilon) = \frac{1}{\pi k_0} \left( \frac{2meF}{\hbar^2} \right)^{1/3} |T_3|^2 \]

Emission current density

\[ J = e \int_0^\infty D(\varepsilon)N(\varepsilon) \, d\varepsilon \]

\[ N(\varepsilon) = \frac{mk_B T}{2\pi^2 \hbar^3} \ln \left[ 1 + \exp \left( \frac{E_F - \varepsilon}{k_B T} \right) \right] \]

where \( N(\varepsilon) \, d\varepsilon \) is the number density of electrons inside metal with longitudinal energy between \( \varepsilon \) and \( \varepsilon + d\varepsilon \) impinging on the surface of metal per unit time [a].


The effects of dielectric properties on electron transmission probability

- Electron transmission probability decreases with $\varepsilon_{\text{die}=l}$
- More resonances for emitters with thicker coating
- Stronger resonances for larger electron affinity
- Electron transmission probability increases with $\chi$

For 1D surface: $F_{\text{die}=l} = F / \varepsilon_{\text{die}=l}$

The effects of dielectric properties on electron transmission probability

- **Resonant peaks** for $d > d_0 \approx \varepsilon_{\text{die}} W / eF$
- Increasing $F$ or $\chi$ shifts the **maximum peak to smaller thickness**
- Increasing $\varepsilon_{\text{die}}$ shifts the **maximum peak to larger thickness**
- **Coated case can induce a transmission probability larger than the bare case**

Potential profile and transmission probability

- The first resonance peak is at \( d_0 \approx \varepsilon_{\text{dielectric}} W/eF \)

- \( D(E_F) \) oscillates around a constant, which is the tunneling probability through a single triangular barrier in thick dielectric.

Potential profile and transmission probability

- **Stronger resonance** is observed for larger electron affinity

Field emission and thermionic emission

\[ J(\varepsilon) = D(\varepsilon)N(\varepsilon) \]

\[ N(\varepsilon) = \frac{mk_BT}{2\pi^2\hbar^3} \ln \left[ 1 + \exp\left( \frac{E_F - \varepsilon}{k_BT} \right) \right] \]

- The model includes not only field emission but also thermionic emission

The effects of dielectric properties on field emission current density

For 1D surface: $F_{\text{dieel}} = F / \varepsilon_{\text{dieel}}$

- $J$ decreases with $\varepsilon_{\text{dieel}}$
- Resonance peaks are not as sharp as in $D(E_F) \text{ vs } \varepsilon_{\text{dieel}}$
- $J$ increases with $\chi$

The effects of dielectric properties on field emission current density

- **Resonant peaks** for $d > d_0 \approx \varepsilon_{\text{die}} W / eF$
- Increasing $F$ or $\chi$ shifts the maximum peak to smaller thickness
- Increasing $\varepsilon_{\text{die}}$ shifts the maximum peak to larger thickness
- Coated case can induce a current density larger than the bare case

Determine the threshold thickness and threshold dielectric constant for current enhancement

- An empirical relation between thickness threshold and dielectric constant threshold at room temperature:

\[ d_{th} \text{[nm]} = \frac{\varepsilon_{\text{die}}^{th} W}{eF} \]

Comparison with modified double-barrier Fowler-Nordheim equation [1-3]

• According to WKB approximation,
  \[ Q(\varepsilon) = 2 \int_0^{x_1} \frac{2m}{\hbar^2} [V(x) - \varepsilon] dx \]

• Electron transmission probability
  \[ D(\varepsilon) = \exp[Q(\varepsilon)] \]

• Electron emission current density
  \[ J = e \int_0^{\infty} D(\varepsilon)N(\varepsilon) \, d\varepsilon \]

Comparison with modified double-barrier Fowler-Nordheim equation [1-3]

- Good agreement in the scaling
- Resonance behavior in $J$ vs. $d$ cannot be revealed by the modified FN equation
Thin dielectric coated plasmonic photoemitter

Plasmonic field confinement
Enhanced fields at Au surface

Electron affinity \( \chi \)
Reduced tunneling barrier

Thin dielectric coated plasmonic photoemitter

For $F = 0.014 - 1$ V/nm, $J$ from the coated photoemitter is enhanced by at least 2 orders of magnitude as compared to the bare emitter.

Thin dielectric coated plasmonic photoemitter

Tunable photoemission at different plasmonic resonant wavelengths

Summary

• An exact analytical quantum model is constructed for electron emission from dielectric coated surfaces.
• Cathodes with coatings of smaller dielectric constant and larger electron affinity tend to emit a larger current density than the bare metal surfaces.
• Empirical relation of the threshold thickness and threshold dielectric constant is proposed.
• The model shows good agreement in scaling with modified double-barrier Fowler-Nordheim equation, but also reveals new resonant peaks.
• Plasmon resonant photoemission from dielectric coated photoemitter is also studied.

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