Theoretical study of field emission from dielectric coated surfaces

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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

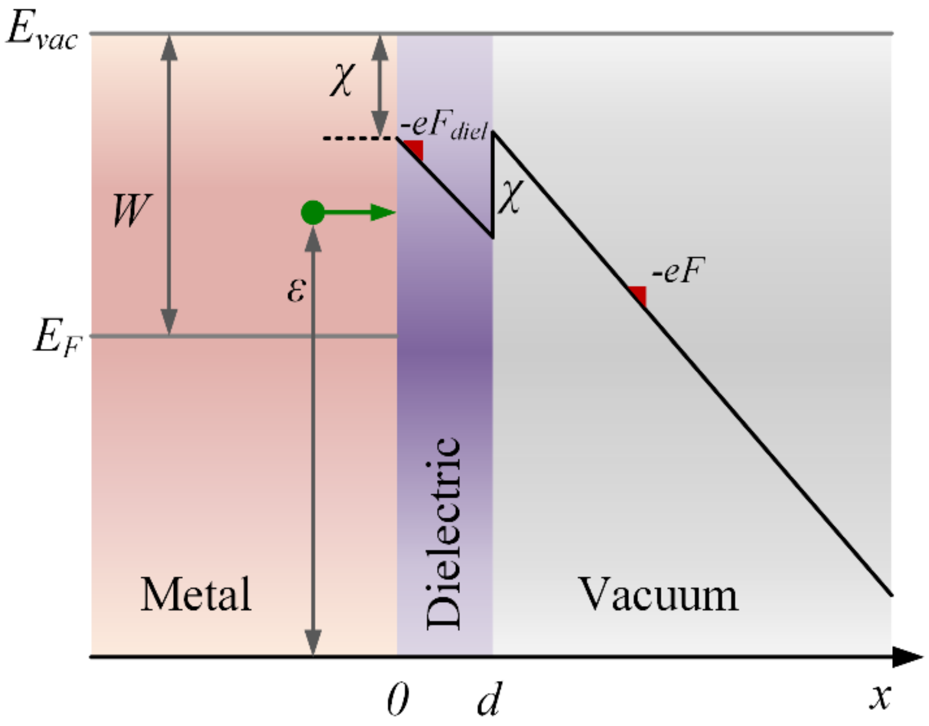
- **Artificial coating**: Ultra-thin coatings are fabricated onto metallic cathodes to provide chemical and mechanical protection, and longer current stability, smaller turn-on electric field and enhanced current emission due to the lowering of the effective potential barrier [1], [2].

- **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]

[1] L. W. Swanson and R. W. Strayer, J. Chem. Phys., 48(6), 2421–2442 (1968).
[2] X. Xiong et al., ACS Nano, 14(7), 8806–8815 (2020).
[3] M. Morita and T. Ohmi, Jpn. J. Appl. Phys. 33, 370 (1994).
[4] G. Wang, P. Yang, N. A. Moody, and E. R. Batista, npj 2D Mater Appl. 2, 17 (2018).

Exact Solution to Schrödinger Equation



Potential barrier

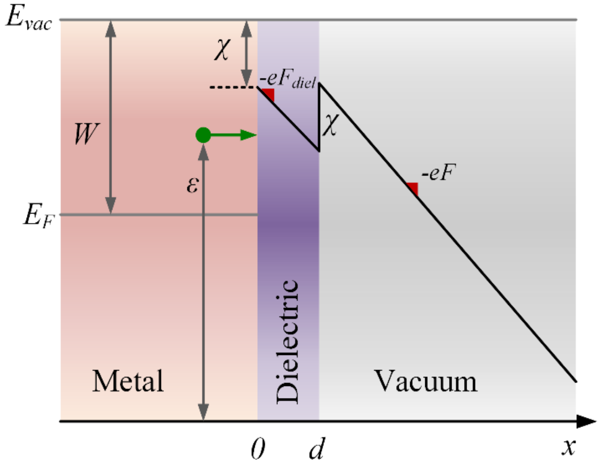
$$V(x) = \begin{cases} 0, & x < 0, \\ E_F + W - \chi - eF_{diel}x, & 0 \le x < d, \\ E_F + W + e(F - F_{diel})d - eFx, & x \ge d. \end{cases}$$

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

$\psi(x)$: complex electron wave function

Y. Zhou and P. Zhang, “Theory of field emission from dielectric coated surfaces”, Phys. Rev. Res., 2, 043439 (2020)

Exact Solution to Schrödinger Equation



x < 0 (Inside metal)

$$\psi_I(x) = e^{ik_0x} + R_1 e^{-ik_0x}$$

Incident plane wave

Reflected waves

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

0 ≤ *x* < *d* (Inside dielectric)

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

$$\eta_1 = \left(\frac{2meF_{diel}}{\hbar^2}\right)^{1/3}\left(x + \frac{\varepsilon - V_1}{eF_{diel}}\right)$$

$$V_1 = W + E_F - \chi$$

x ≥ *d* (Vacuum Region)

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

$$\eta_2 = \left(\frac{2meF}{\hbar^2}\right)^{1/3}\left(x + \frac{\varepsilon - V_2}{eF}\right)$$

$$V_2 = W + E_F + e(F - F_{diel})d$$

Exact Solution to Schrödinger Equation

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

$$\left.\begin{aligned}
\psi_I(x=0) &= \psi_{II}(x=0) \\
\left.\frac{\partial \psi_I}{\partial x}\right|_{x=0} &= \left.\frac{\partial \psi_{II}}{\partial x}\right|_{x=0} \\
\psi_{II}(x=d) &= \psi_{III}(x=d) \\
\left.\frac{\partial \psi_{II}}{\partial x}\right|_{x=d} &= \left.\frac{\partial \psi_{III}}{\partial x}\right|_{x=d}
\end{aligned}\right\} \Longrightarrow \boldsymbol{R_1}, \textbf{a}, \boldsymbol{b}, \& \boldsymbol{T_3}$$

Electron transmission probability

$$D(\varepsilon) = \frac{J_3(\varepsilon)}{J_i(\varepsilon)}$$

with $J = \frac{i\hbar}{2m}(\psi \nabla \psi^* - \psi^* \nabla \psi)$

Exact Solution to Schrödinger Equation

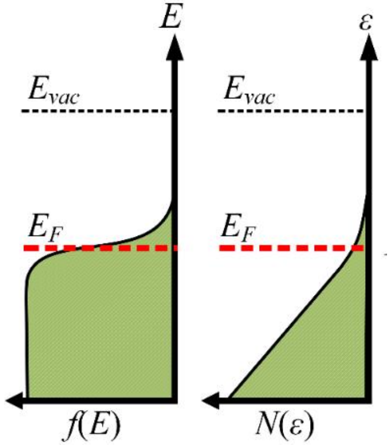
Electron transmission probability

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

Emission current density

$$J = e\int_0^{\infty} D(\varepsilon)N(\varepsilon)\, d\varepsilon$$

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

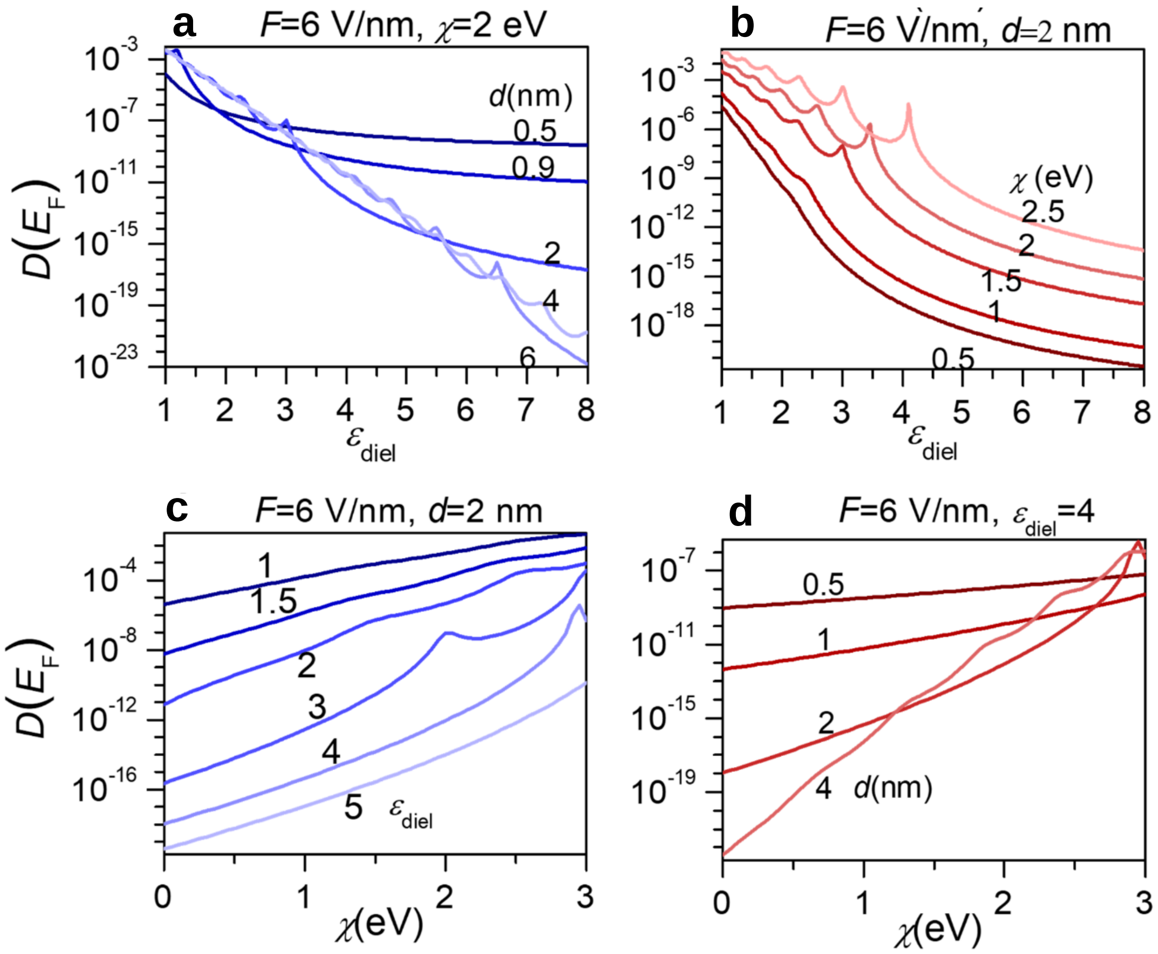


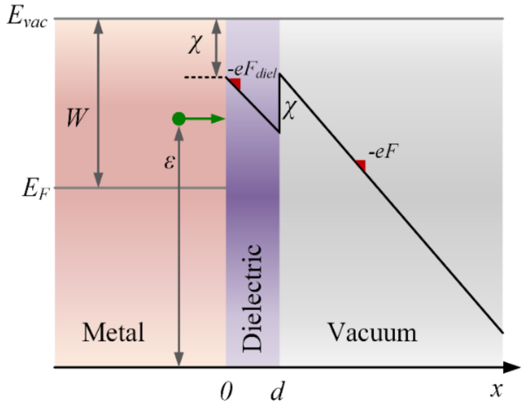
where $N(\varepsilon)d\varepsilon$ is the number density of electrons inside metal with longitudinal energy between ε and $\varepsilon+d\varepsilon$ impinging on the surface of metal per unit time [a].

Y. Zhou and P. Zhang, "Theory of field emission from dielectric coated surfaces", Phys. Rev. Res., 2, 043439 (2020)

[a] K. L. Jensen, Introduction to the Physics of Electron Emission, 1 edition (Wiley, Hoboken, New Jersey, 2017).

The effects of dielectric properties on electron transmission probability





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

- Electron transmission probability decreases with ε_{diel}
- **More resonances** for emitters with thicker coating
- **Stronger resonances** for larger electron affinity
- Electron transmission probability increases with χ

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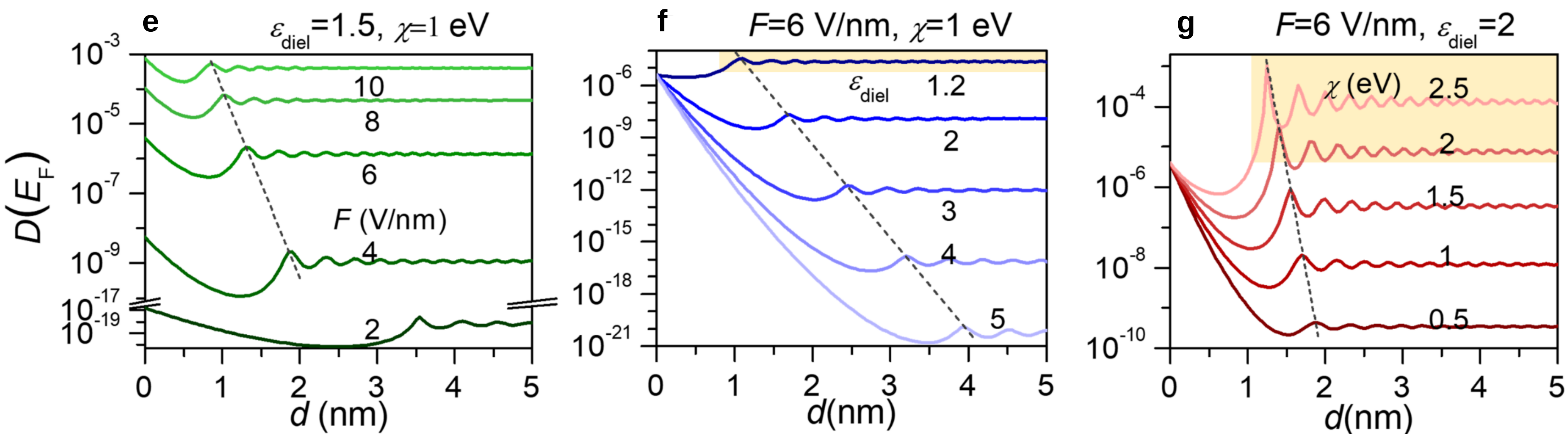
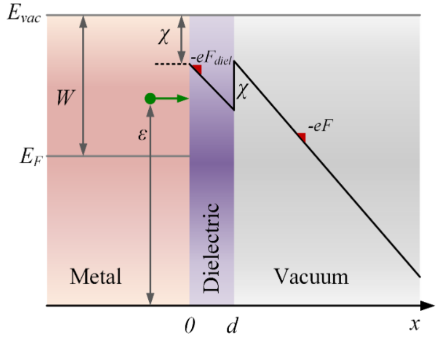
The effects of dielectric properties on electron transmission probability



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



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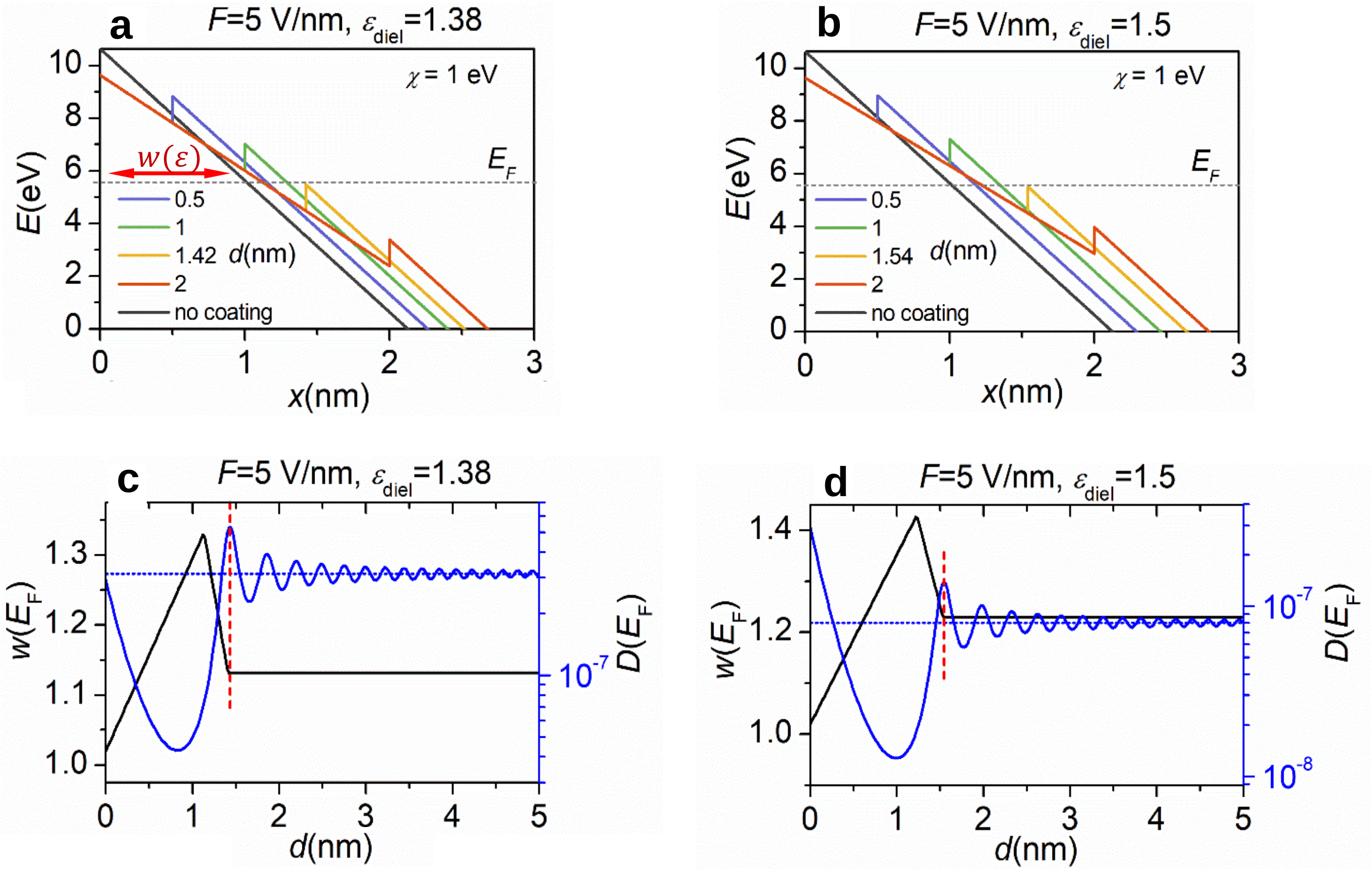
Potential profile and transmission probability



- The first resonance peak is at $d_0 \approx \varepsilon_{diel} W/eF$

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

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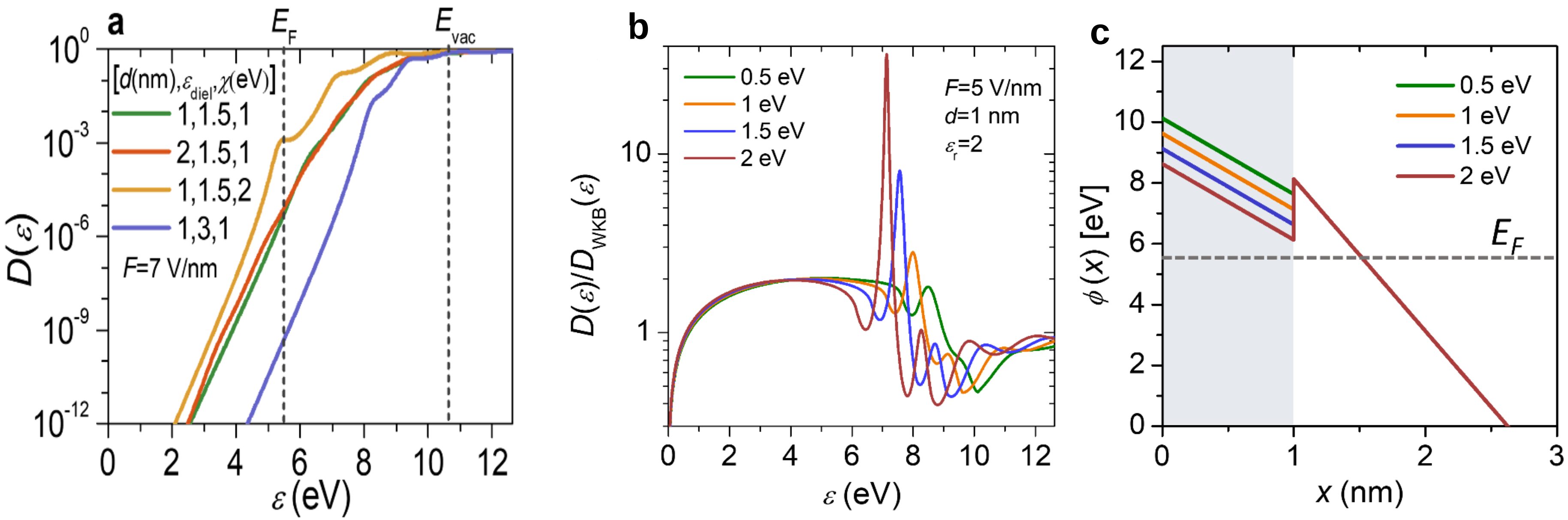
Potential profile and transmission probability



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

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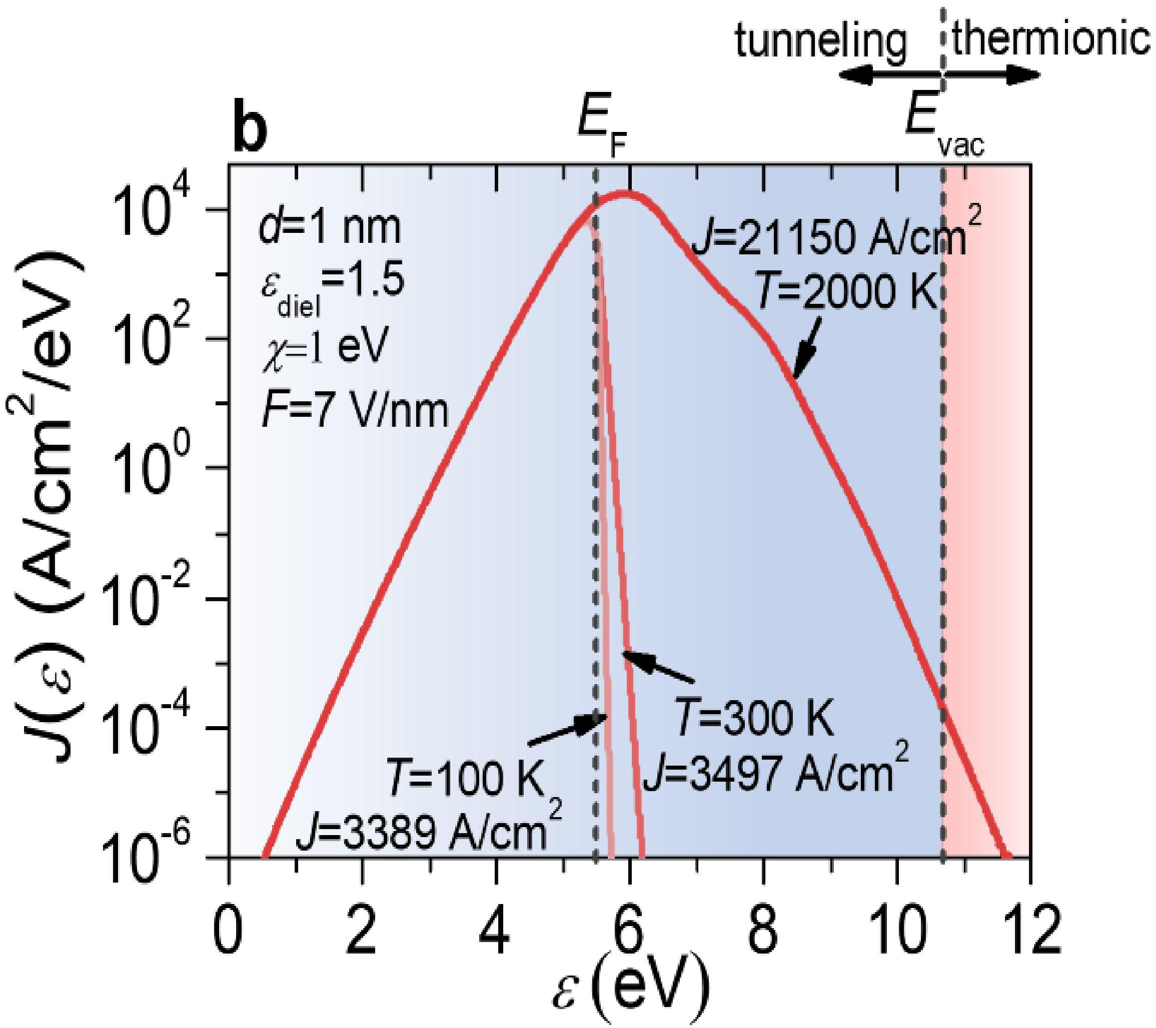
Field emission and thermionic emission



$$J(\varepsilon) = D(\varepsilon)N(\varepsilon)$$

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

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

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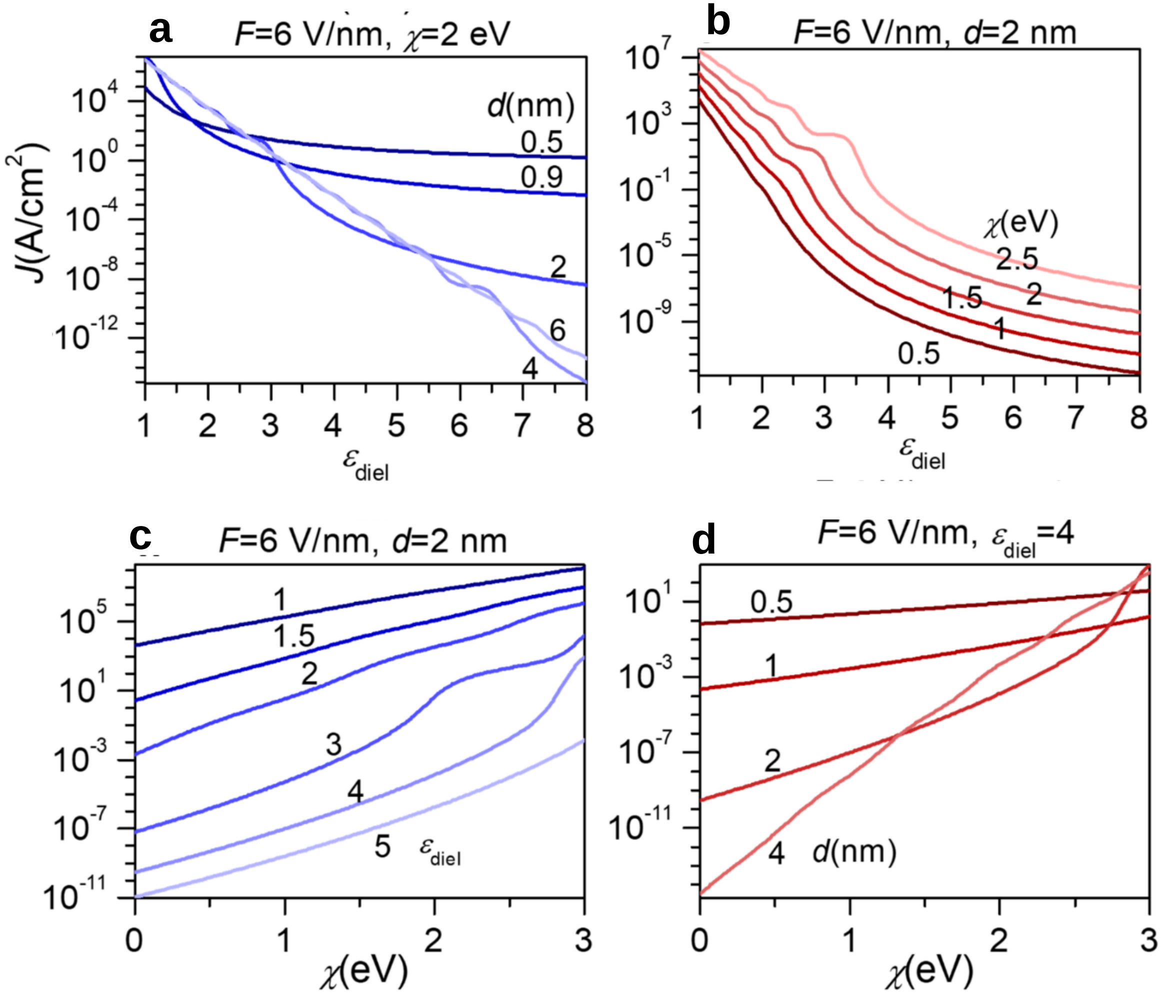
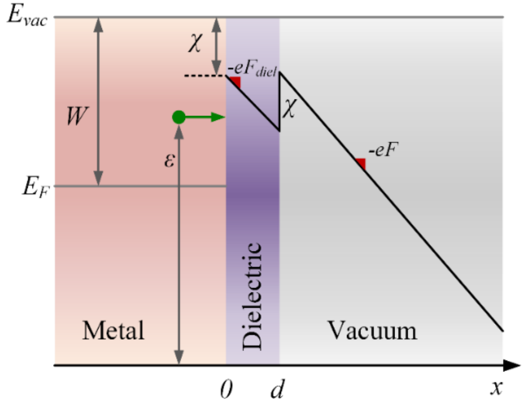
The effects of dielectric properties on field emission current density





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

- J decreases with ε_{diel}
- Resonance peaks are not as sharp as in $D(E_F)$ vs ε_{diel}
- J increases with χ

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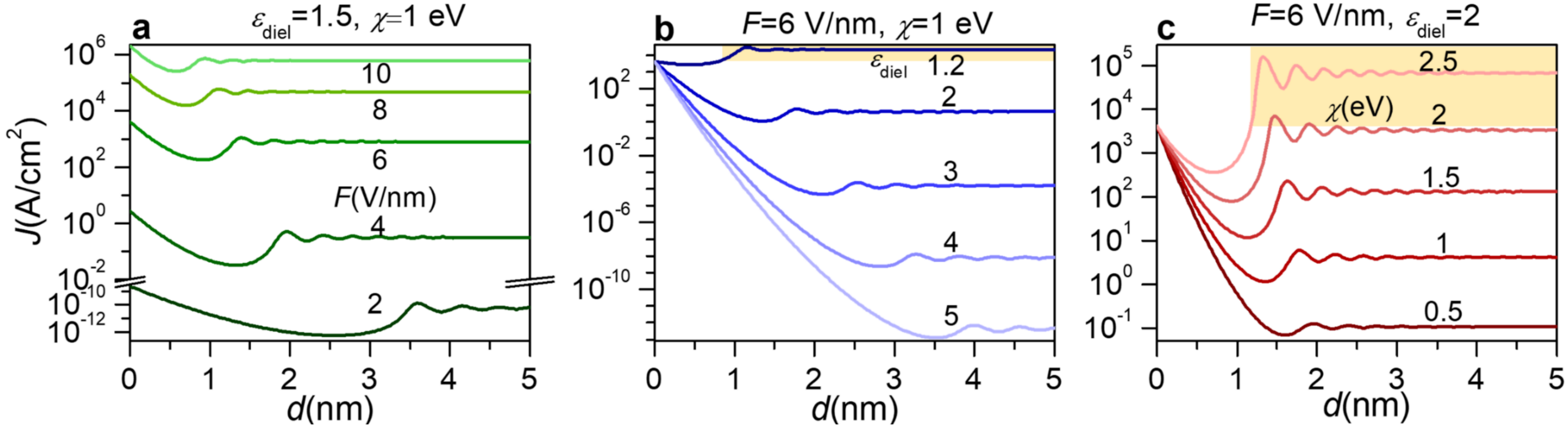
The effects of dielectric properties on field emission current density



- **Resonant peaks** for $d > d_0 \approx \varepsilon_{diel} W / eF$
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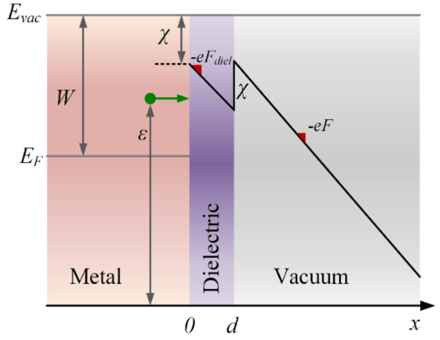

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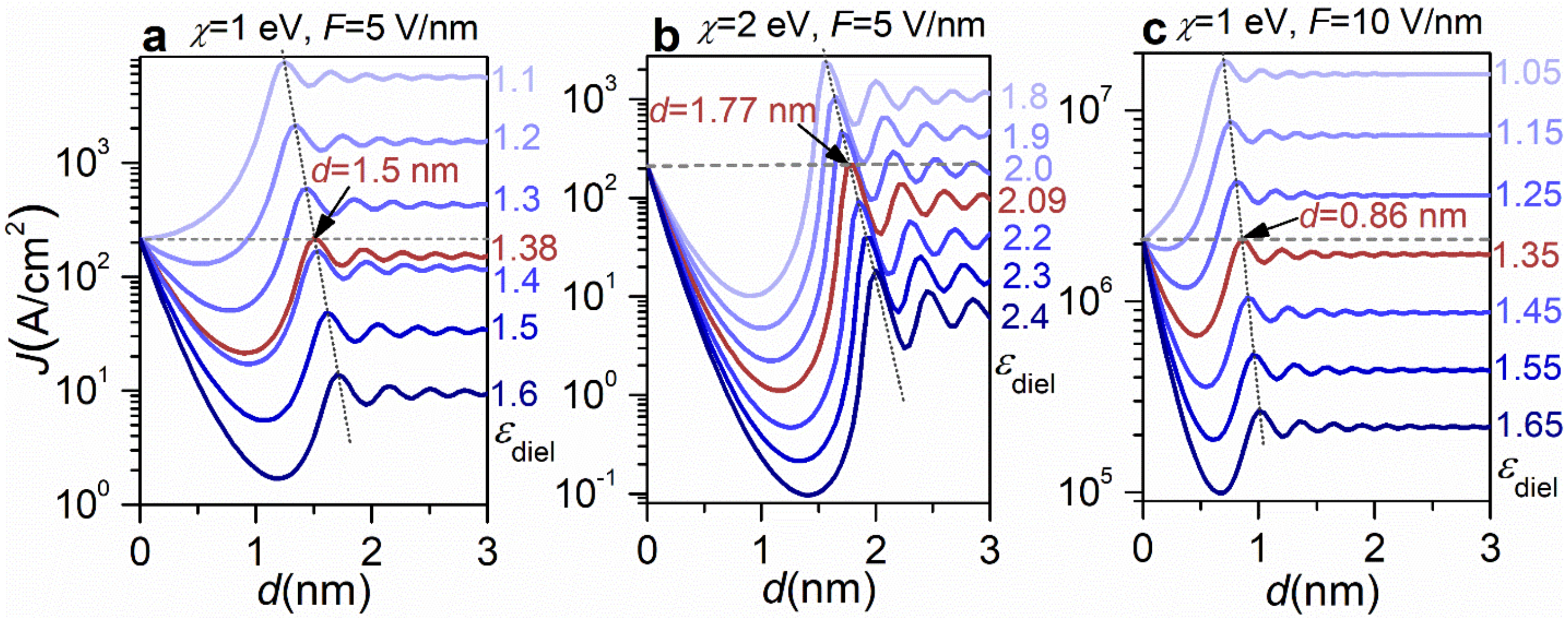
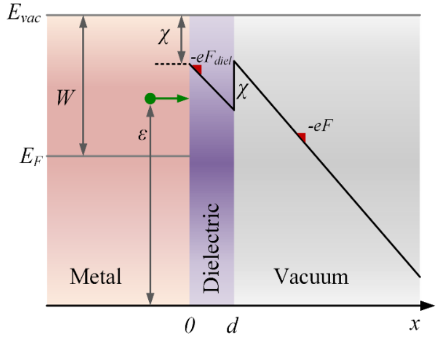
Determine the threshold thickness and threshold dielectric constant for current enhancement



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

$$\boxed{d_{th}[\mathrm{nm}] = \frac{\varepsilon_{diel}^{th} W}{eF}}$$



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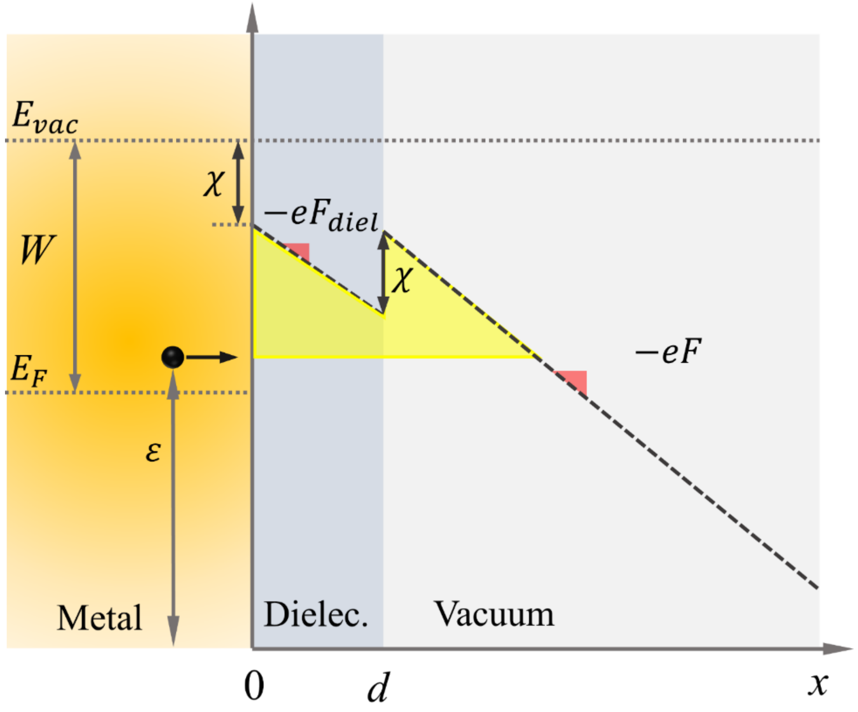
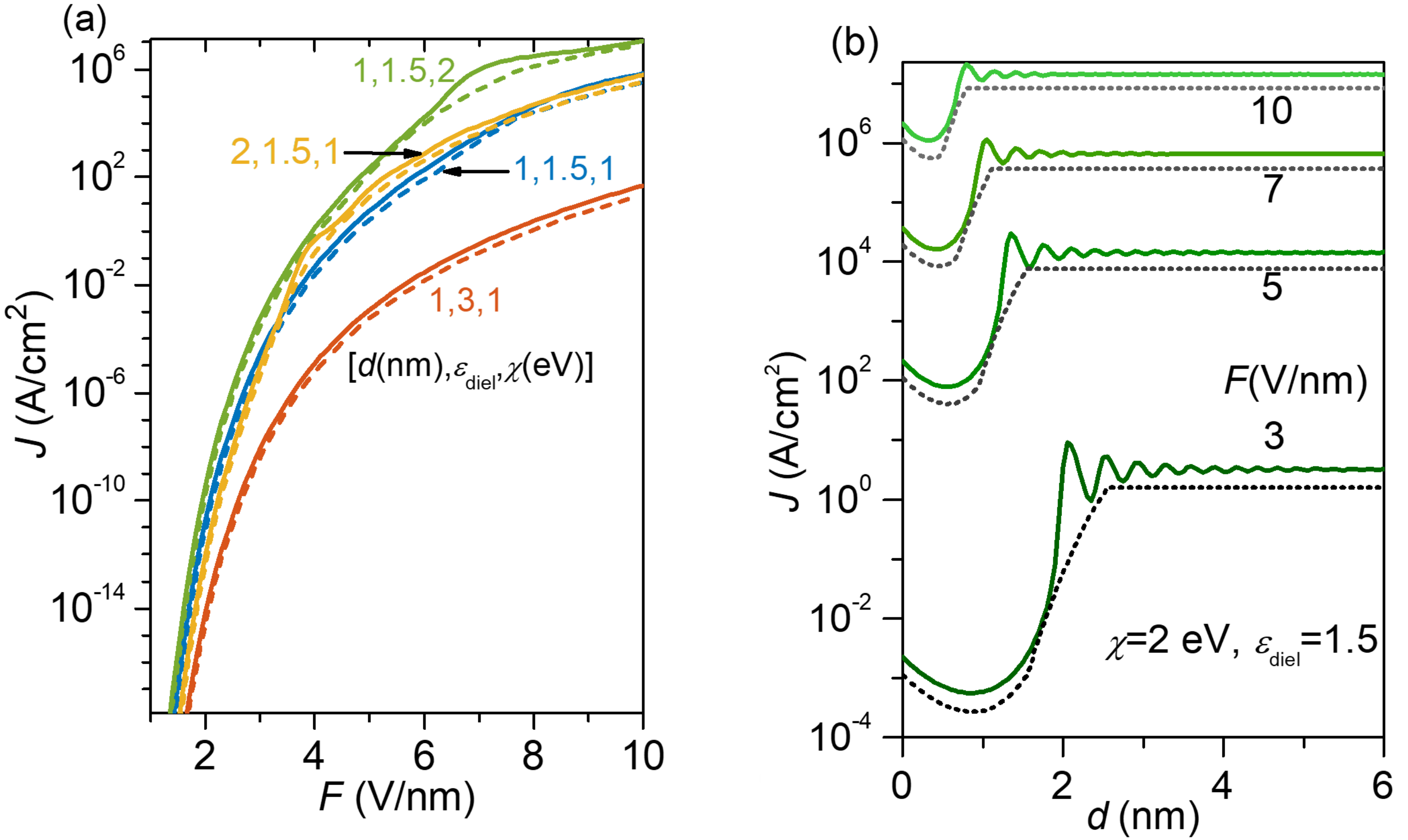
Comparison with modified double-barrier Fowler-Nordheim equation [1-3]



- According to WKB approximation, $$Q(\varepsilon) = 2\int_0^{x_1} \sqrt{\frac{2m}{\hbar^2}[V(x) - \varepsilon]dx}$$
- Electron transmission probability $$D(\varepsilon) = \exp[Q(\varepsilon)]$$
- Electron emission current density $$J = e\int_0^{\infty} D(\varepsilon)N(\varepsilon)\, d\varepsilon$$

[1] Q.-A. Huang, J. Appl. Phys. 79(7), 3703-3707, (1996).
[2] P. D. Keathley et al., Ann. Phys., 525(1–2), 144–150 (2013).
[3] K. L. Jensen, et al., J. Appl. Phys. 127(23), 235301, (2020).

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

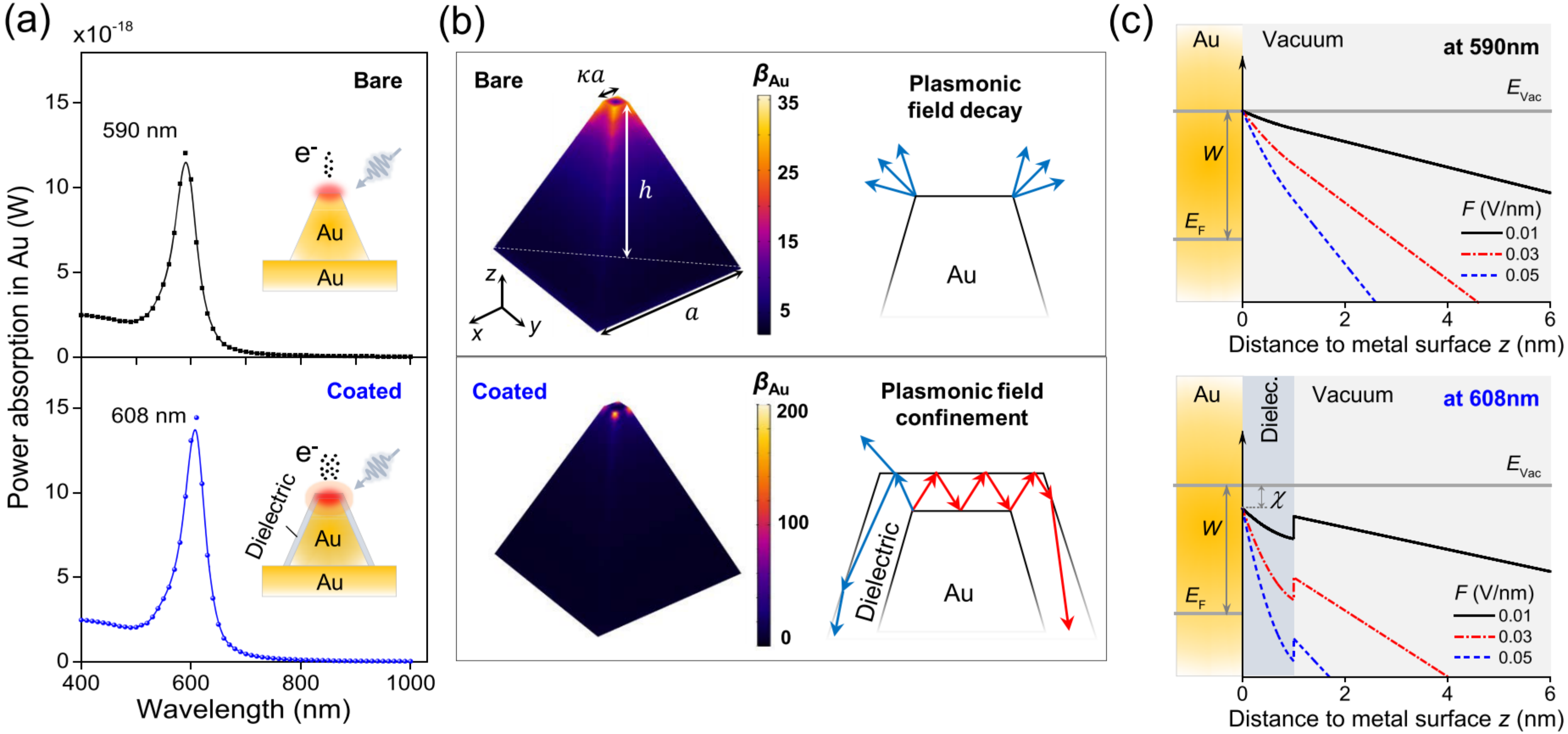
Thin dielectric coated plasmonic photoemitter

Plasmonic field confinement

Enhanced fields at Au surface

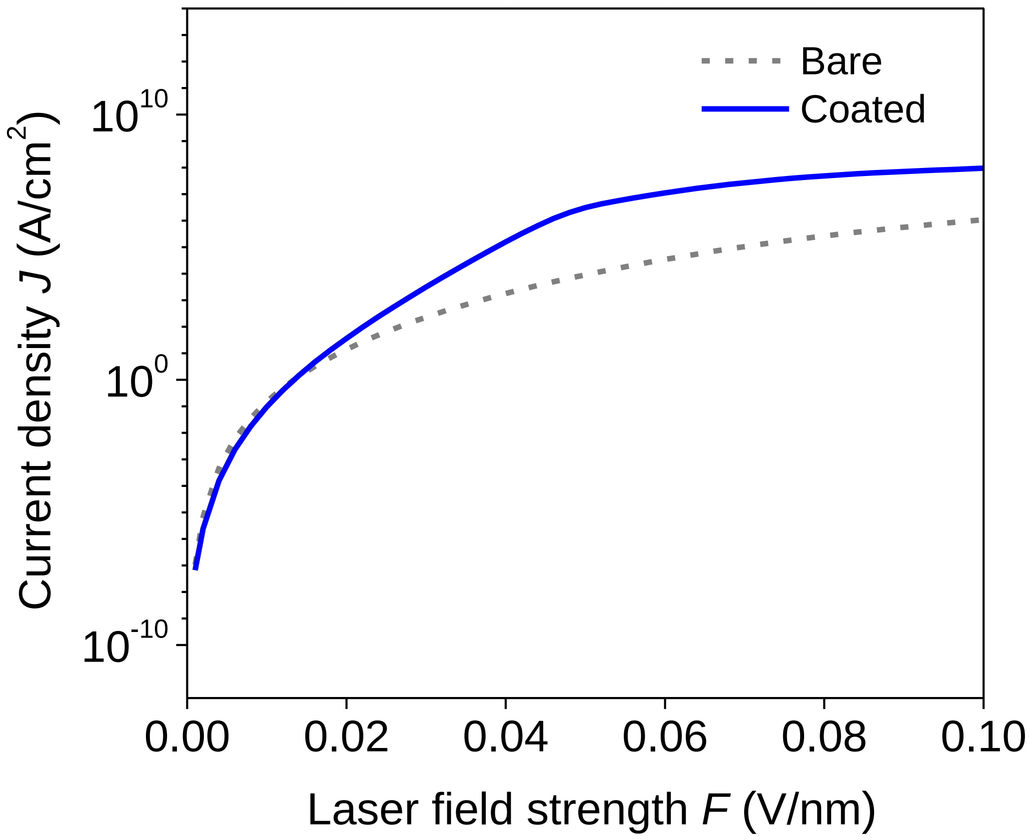
Electron affinity χ

Reduced tunneling barrier



X. Xiong, Y. Zhou, Y. Luo, X. Li, M. Bosman, L. K. Ang, P. Zhang, and L. Wu, "Plasmon-Enhanced Resonant Photoemission Using Atomically Thick Dielectric Coatings", ACS Nano, 14, 8806 − 8815 (2020).

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.

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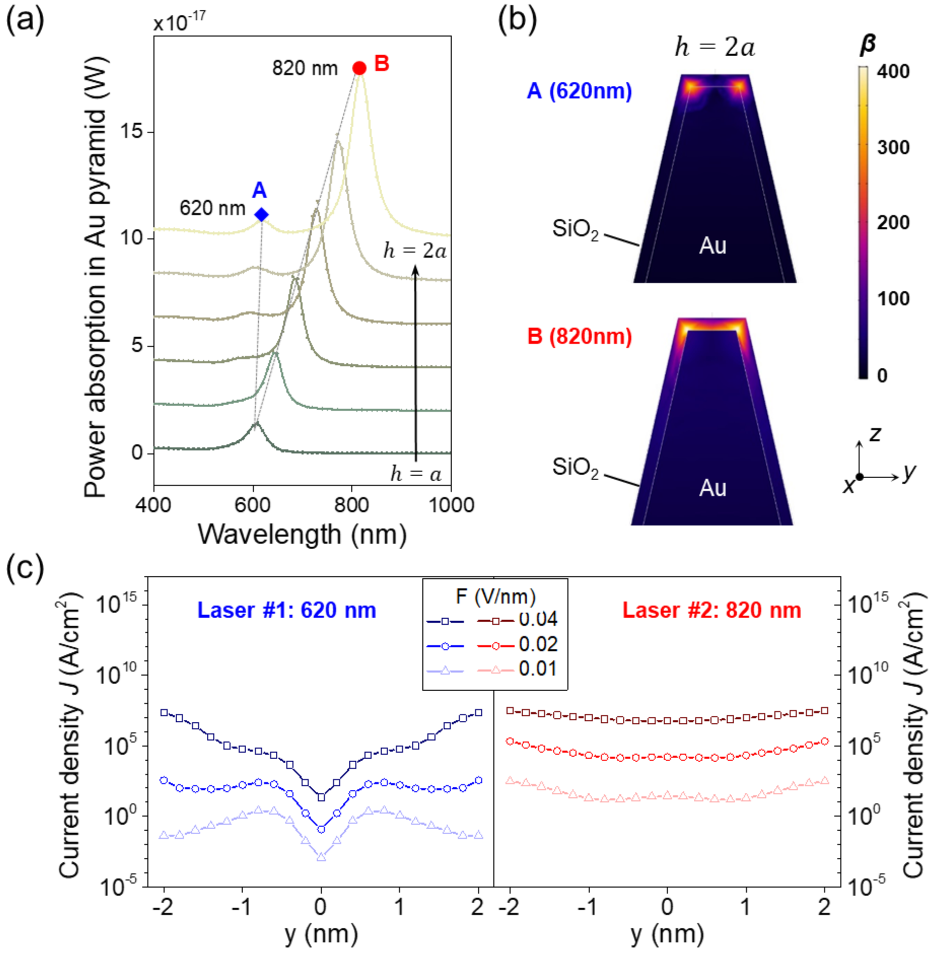
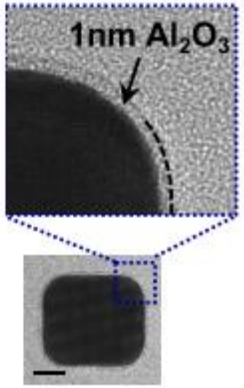


Tunable photoemission at different plasmonic resonant wavelengths



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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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