Photon-Assisted Thermionic Emission: A Theoretical Prediction for Photoelectron Energy Spectra, Emission Current, and QE

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I. Background

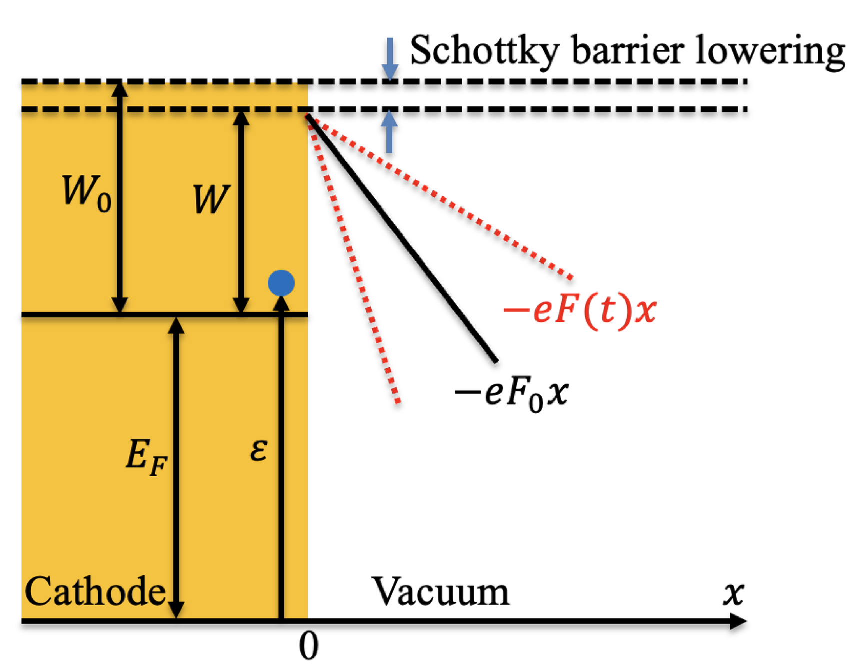
1. Electron emission is important to many applications ranging from accelerators and ultrafast electron diffraction/microscopy to high-power microwave sources and electric-propulsion cathodes.
2. Photon-assisted thermionic emission (PATE) leverages optical excitation to amplify electron release from heated cathodes, enabling higher current density at a given temperature—or equivalent performance at lower heater power—than dark thermionic emission alone.
3. In RF/DC electron guns, microwave tubes, and propulsion cathodes, optical assistance can reduce warm-up time and heater load, relax vacuum requirements at a fixed current density, and help preserve cathode lifetime by lowering operating temperature [1-2].

In this work, we investigate PATE from tungsten (W) and lanthanum hexaboride (LaB_6)—refractory emitters with different work functions—using a quantum model that solves the one-dimensional Schrödinger equation exactly [3-4].

II. Theoretical Formulation [3-5]

➢ Potential profile:

$$\Phi(x,t)=\begin{cases}0, & x<0\\ E_F+W-eF_0x-eF(t)x & x\geq 0\end{cases}$$



W_0: work function of the cathode

W: effective work function

E_F: Fermi energy

ε: the initial electron energy

e: electron charge

F_0: DC field

$F(t)=F_1\cos\omega t$: laser field

➢ 1D Time-dependent Schrödinger equation:

$$i\hbar\frac{\partial\psi(x,t)}{\partial t}=-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial t^2}+\Phi(x,t)\psi(x,t)$$

➢ Emission current density at electron initial energy ε can be obtained:

$$w(\varepsilon,x,t)=\frac{j_t}{j_i}, \qquad (4)$$

where $j=\frac{i\hbar}{2m}(\psi\nabla\psi^*-\psi^*\nabla\psi)$, j_t / j_i is transmitted / incident probability current density.

➢ The time-averaged electron transmission probability from the energy level of ε,

$$D(\varepsilon)=\sum_{n=-\infty}^{\infty}w_n(\varepsilon),$$

where $w_n(\varepsilon)$ denotes the electron transmission probability through the n-photon process.

➢ The total emission current density:

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

where $N(\varepsilon)=\frac{mk_BT}{2\pi^2\hbar^3}\ln[1+\exp\left(\frac{E_F-\varepsilon}{k_BT}\right)]$ is the supply function derived from the free electron model for metal, and $J_{spectrum}(\varepsilon_{emitted})$ is the differential current density per energy (A/cm^2eV), which represents the emitted photoelectron energy spectrum with $\varepsilon_{emitted}=\varepsilon+n\hbar\omega$ the emitted electron energy.

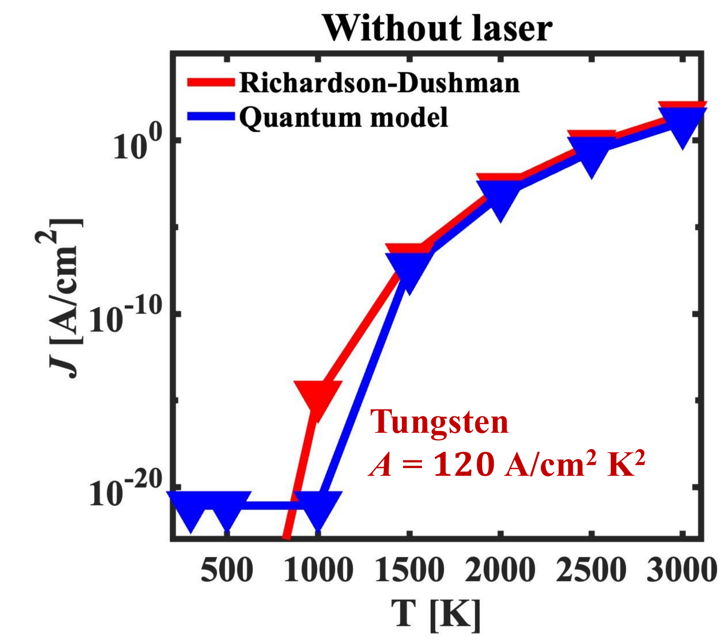
➢ Quantum efficiency (QE)

$$QE=\frac{J/e}{I/\hbar\omega},$$

where $I=\varepsilon_0cF_1^2/2$ is the incident laser intensity, with c the speed of light in vacuum.

III. Results

➢ Compare J as a function of T from quantum model to from Richardson-Dushman formula.



Richardson-Dushman Equation:

$$J=AT^2e^{-\phi/k_BT}$$

TABLE I. Key parameters for thermionic materials and common laser wavelengths/energies.

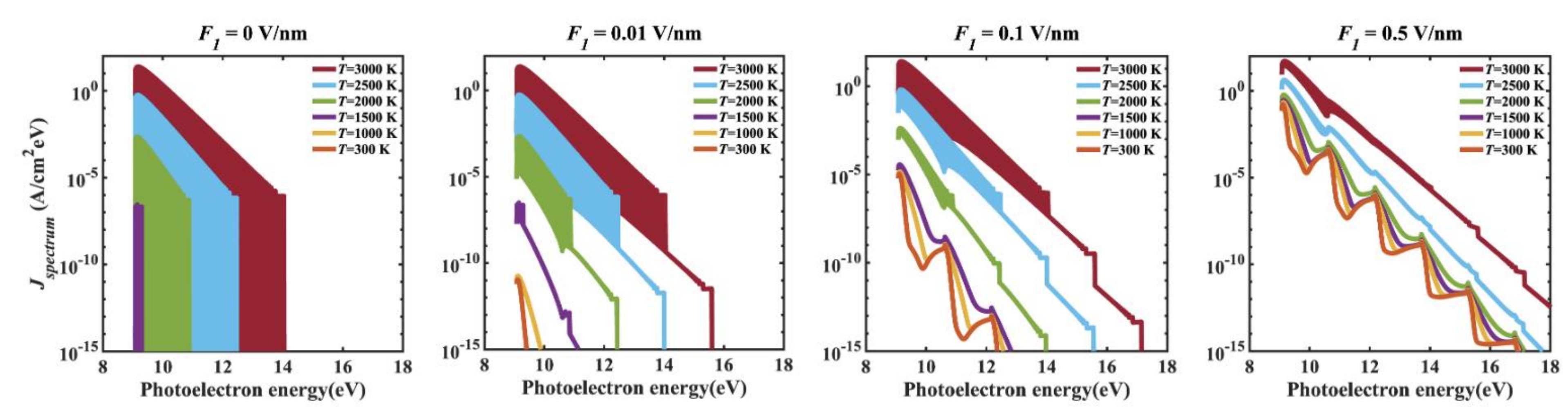
	Tungsten	LaB_6	CeB_6
Work function [eV]	4.52	2.70	2.65
Richardson constant [$Acm^{-2}K^{-2}$]	120	29	3.9
Melting point [K]	3695	2483	2463

Common laser wavelengths and photon energies

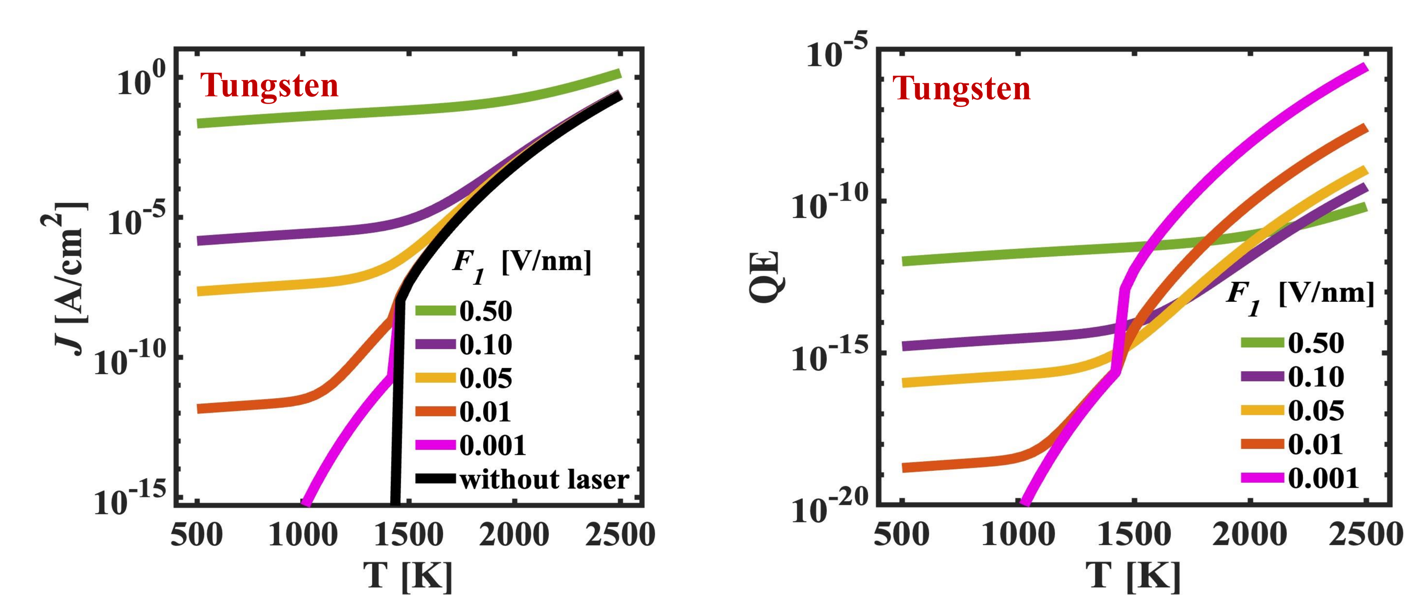
Wavelength [nm]	800	532	405	355	266
Photon energy [eV]	1.55	2.33	3.06	3.49	4.66

The properties of LaB6 and CeB6 are from Ref [6].

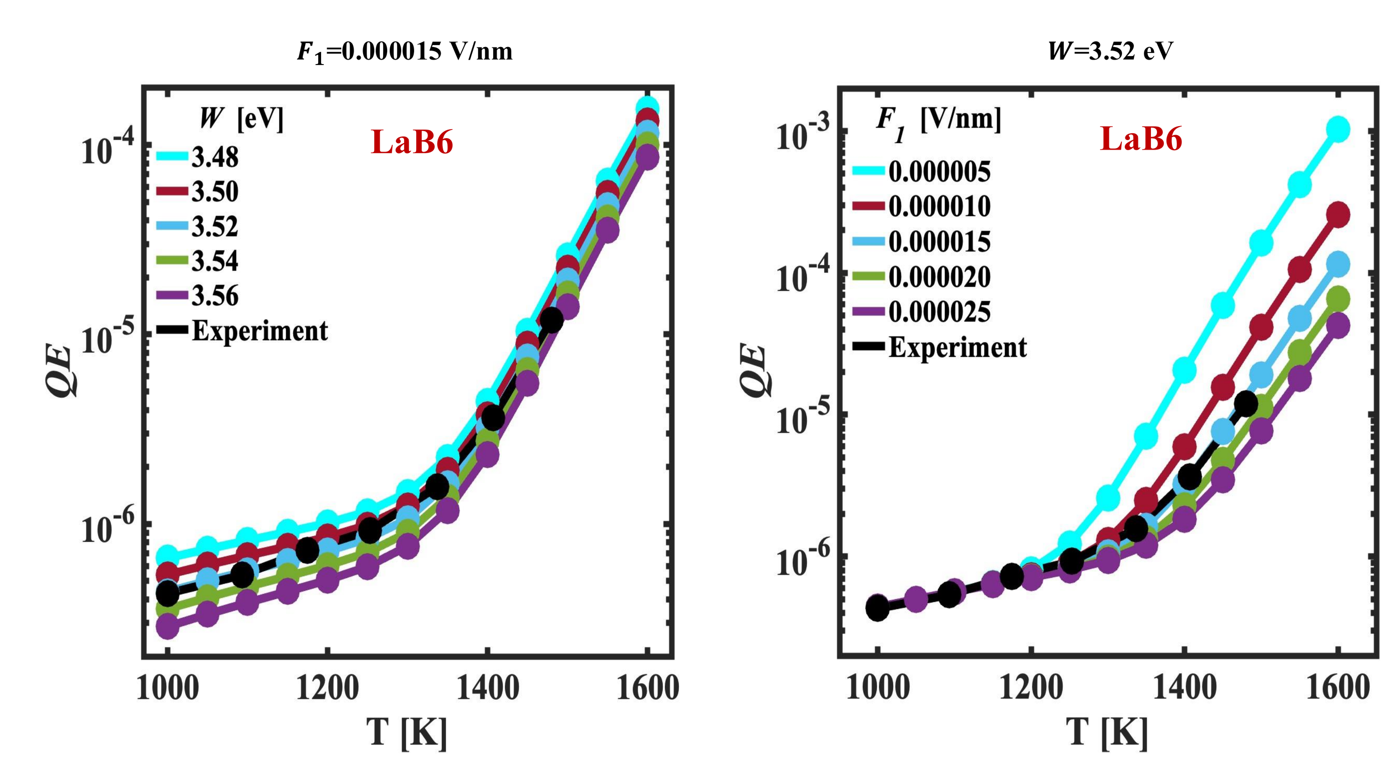
➢ Emission energy spectra of Tungsten (λ = 800 nm)



➢ Emission current density and QE



➢ QE in varying work functions and varying peak laser strengths (λ = 355 nm)



Experiment data is from reference [1].

IV. Conclusion

1. The emission energy spectrum can be tuned by varying the laser intensity, wavelength, and cathode temperature. Increasing the peak laser field and using shorter wavelengths both enhance the emission spectrum and reduce the relative differences between spectra at different temperatures. **Photon-assisted thermionic emission (PATE) can substantially increase the overall emission and broaden the energy distribution.**

2. At low temperature, laser illumination can strongly enhance the emitted current from the hot cathode, demonstrating the improved performance and characteristic behavior of photon-assisted thermionic emission.

3. **Increasing the cathode temperature enhances thermionic emission and therefore increases the quantum efficiency (QE),** since a larger fraction of electrons in the thermal tail can overcome the emission barrier.

4. For PATE, the inclusion of temperature as a control parameter provides greater flexibility in tailoring and enhancing the QE.

References

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