# Ultrafast and Nanoscale Diodes

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Solved and Unsolved Problems in Plasma Physics
A Symposium in Honor of Nathaniel J. Fisch
PPPL
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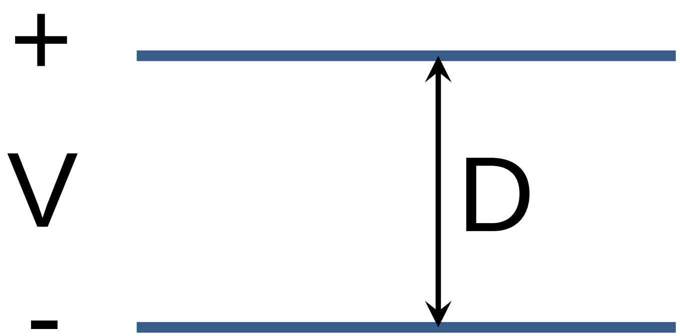
Supported by AFOSR




Diode

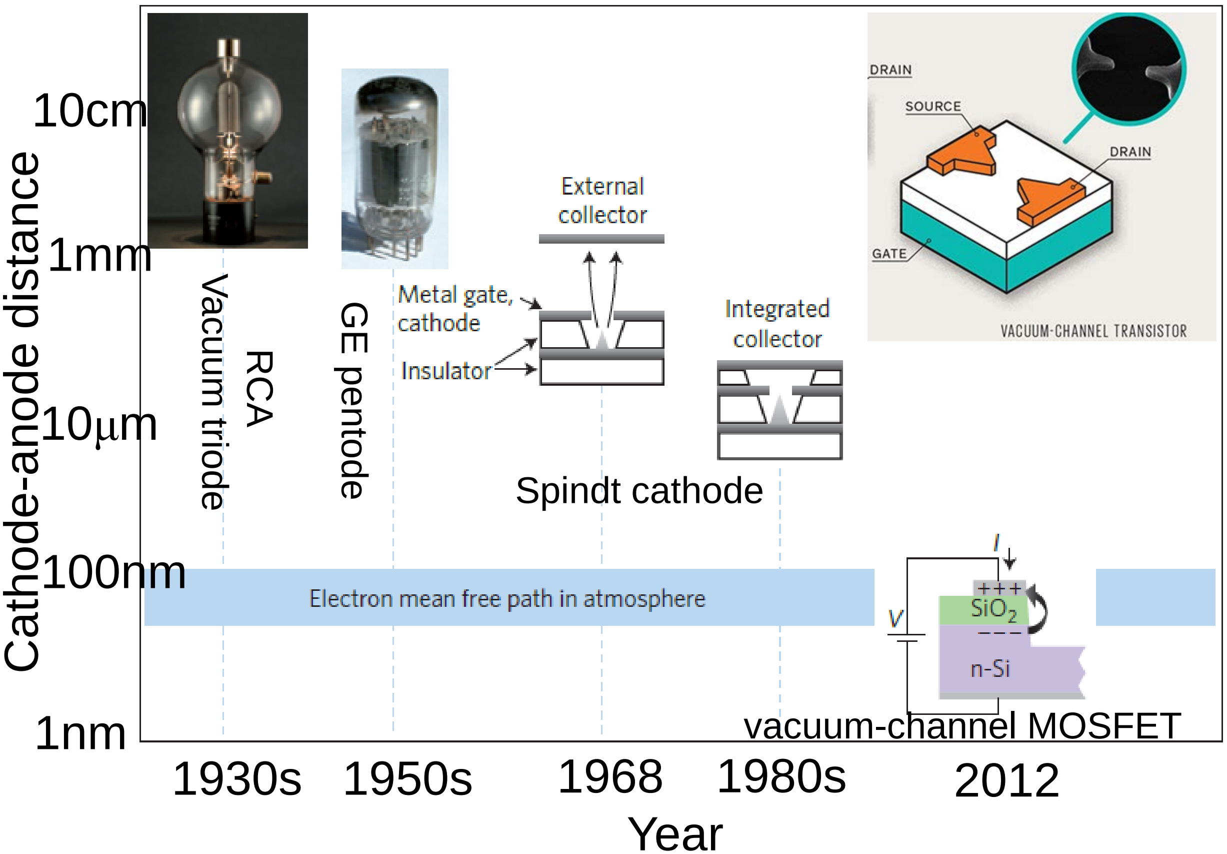
$$J_{CL} = \frac{4\sqrt{2}}{9}\varepsilon_0\sqrt{\frac{e}{m}}\frac{V^{3/2}}{D^2}$$

Child-Langmuir Law

Short bunch?
Quantum?
Electron emission process: Field emission?
Photoemission?
Intense beam with $B_{ext}$ + $B_{self}$?
3D effects?

# The emergence of vacuum and plasma nano-devices

Evolution of Vacuum electronics




- Vacuum is intrinsically a better carrier transport medium than solid
  - Vacuum: ballistic transport
  - Solid: optical and acoustic phonon scattering

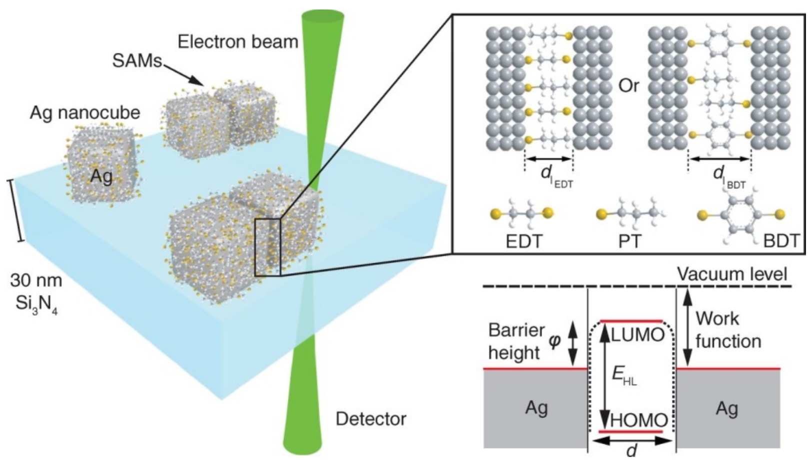
Integration of miniature vacuum electronic devices with solid-state platforms, thus combines the advantages of ballistic transport through vacuum with the scalability, low cost and reliability of conventional silicon transistor technology

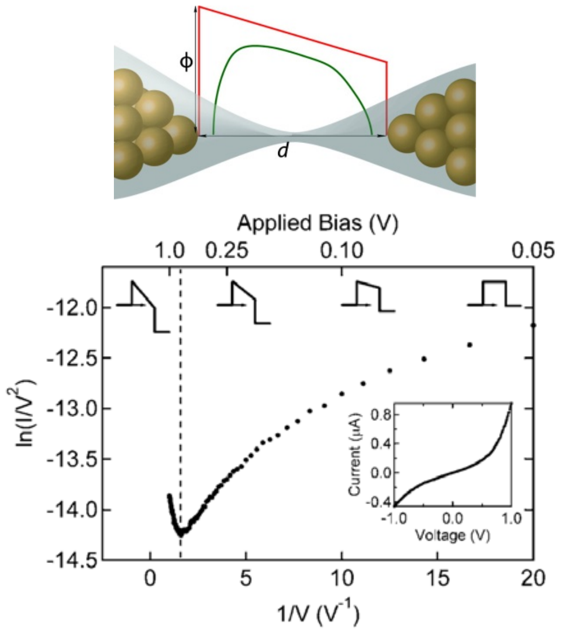
Stoner and T. Glass, Nat. Nanotech 7, 485 (2012).
Srisonphan, Jung and Kim, Nat. Nanotech 7, 504 (2012).
Han and Meyyappan, IEEE Spectrum, 23 Jun 2014.



UNIVERSITY OF MICHIGAN

# Quantum Tunneling Junctions



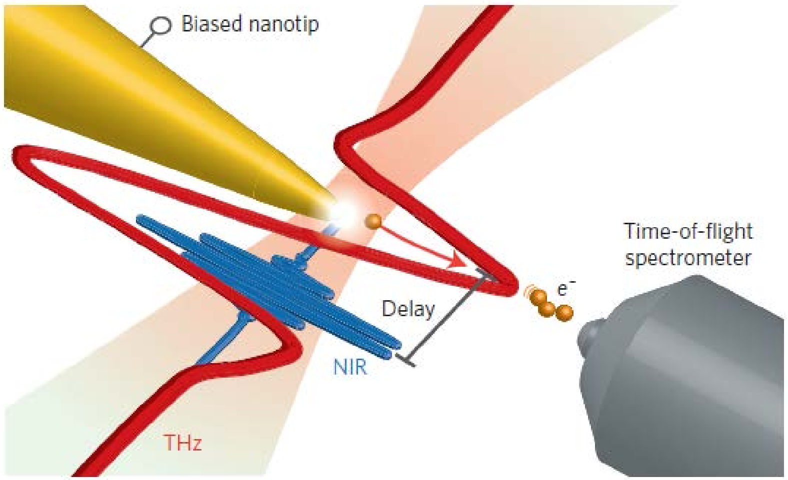

Electron tunneling between plasmonic resonators is recently found to support **quantum plasmon resonances**

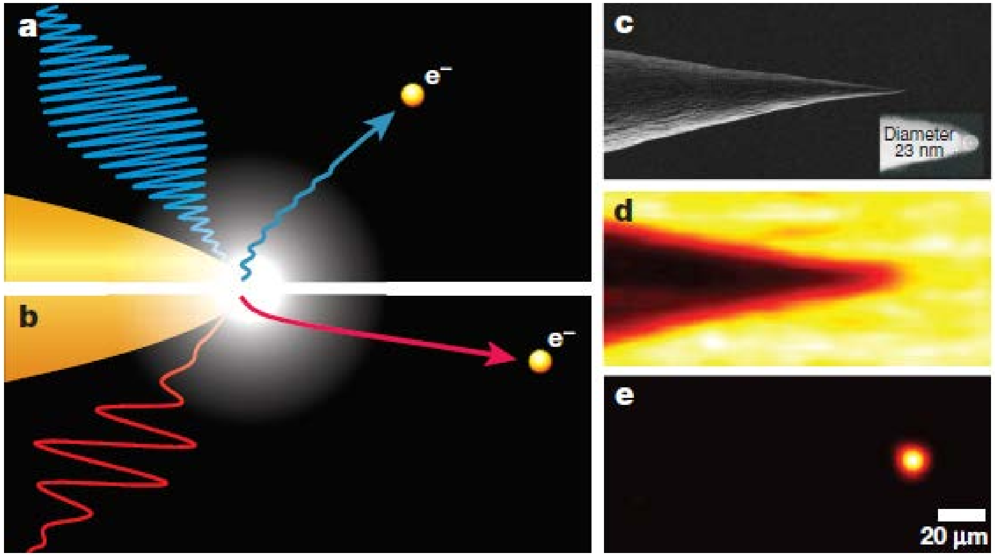
Tan, S. F. et al., Science 343, 1496 (2014).

**Transition voltage spectroscopy (TVS)** is proposed to determine the tunneling barrier height

Beebe, J. M. et al., PRL 97, 026801 (2006).
Trouwborst, M. L. et al. Nano Lett. 11, 614 (2011).

# Ultrafast Electron Emission




Terahertz control of nanotip photoemission

Wimmer, Herink, Solli, Yalunin, Echternkamp and Ropers, Nat. Phys. 10, 432 (2014).

Field-driven photoemission from nanostructures quenches the quiver motion

Herink, Solli, Gulde, Ropers, Nat. 483, 190 (2014).

Attosecond Science!

# Ultrafast and Nanoscale Interfacial Charge Transport

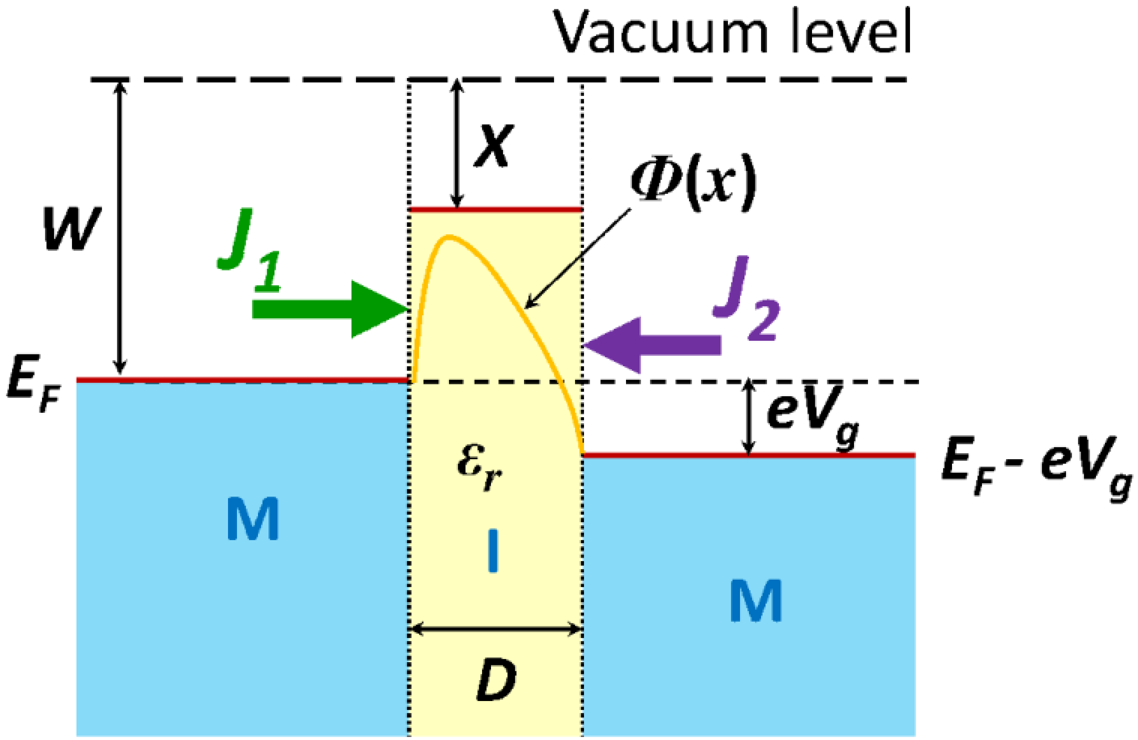
- The understanding of the underlying physics is limited.

- Scaling laws are largely unexplored.

**Recent modeling efforts:**

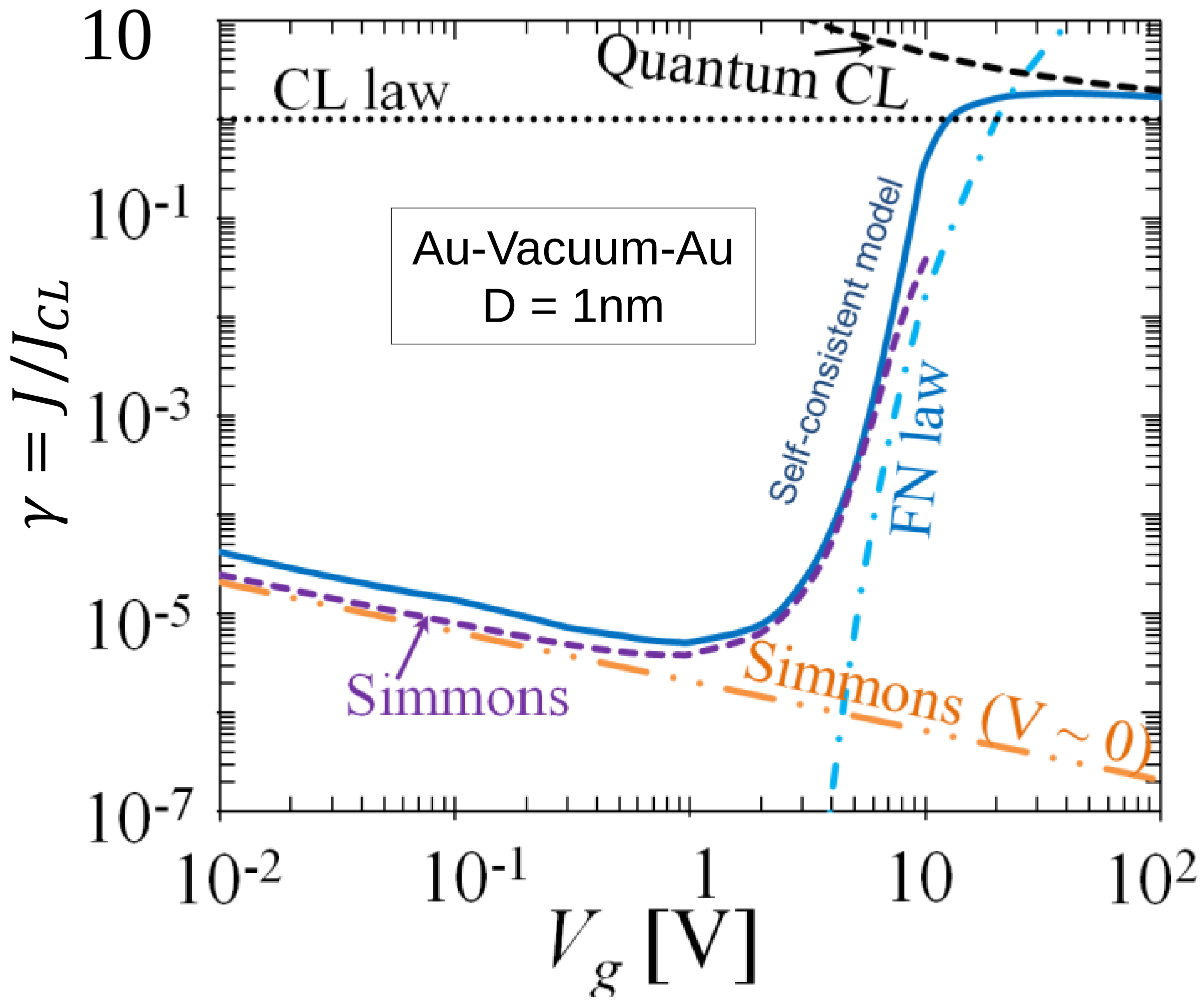
1. **Quantum tunneling**
2. **Ultrafast electron emission and transport**
3. **Current crowding and contact resistance**

# Nanoscale Diode
## -Self-consistent Model




Given $W$, $E_F$, $\epsilon_r$, $D$, $V_g$ $\Longrightarrow$ $\Phi(x), J_1, J_2, J_{net} = J_1 - J_2$

# Scaling for Tunneling Current



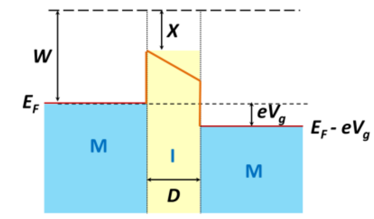

**Direct Tunneling** | **Field Emission** | **Space Charge Limited**

P. Zhang, Sci. Rep., 5, 9826 (2015).

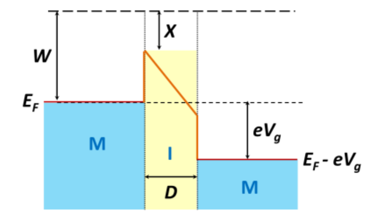
Limiting cases:

- Simmons formula

  Simmons, JAP, 34, 1793 (1963).

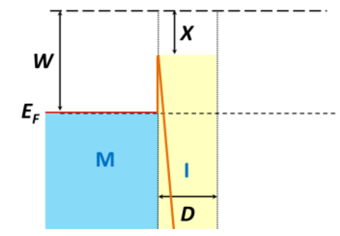



- Fowler-Nordheim (FN) field emission

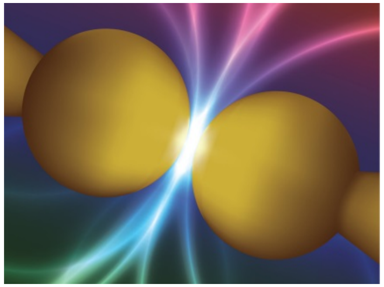



- Child-Langmuir (CL) law
- Quantum CL law

  Lau, et al, PRL 66, 1446 (1991).
  Ang, et al, PRL 91, 208303 (2003).



# Application to Charge Transfer Plasmon (CTP) Tunneling Junctions



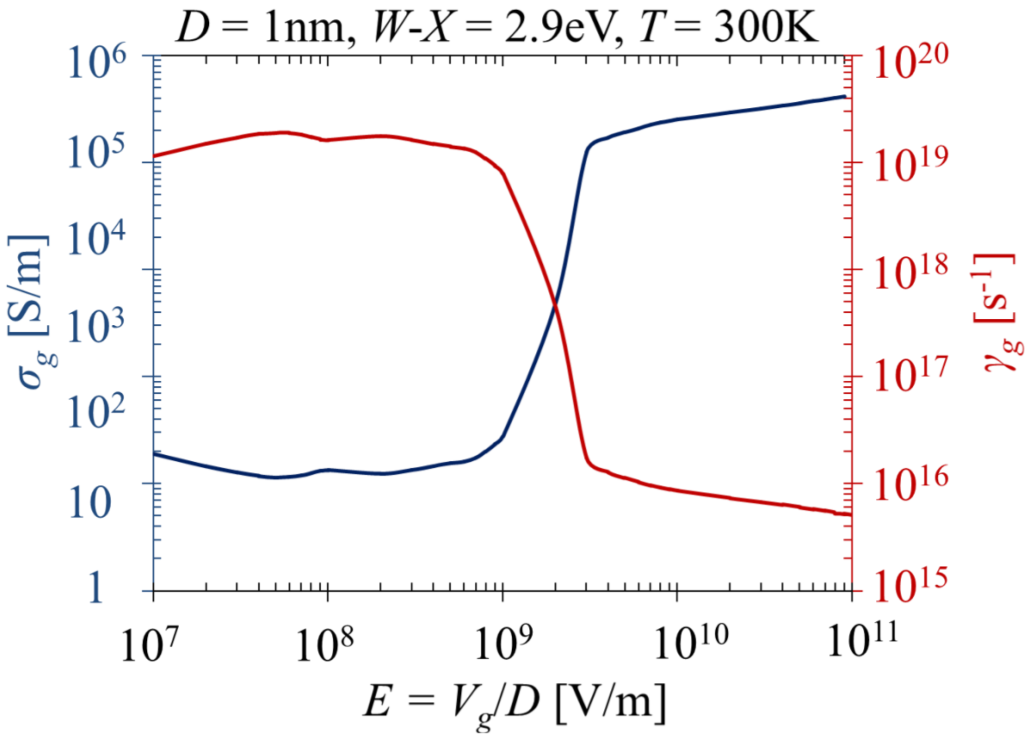
Gap tunneling conductivity $\sigma_g$

$$\sigma_g = J_{net}/V_g$$

Tunneling damping parameter $\gamma_g$

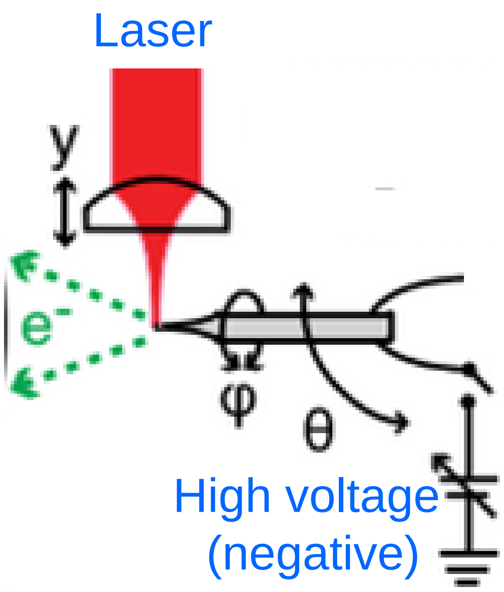
$$\epsilon_g(\omega) = 1 + i\sigma_g/\omega\epsilon_0$$

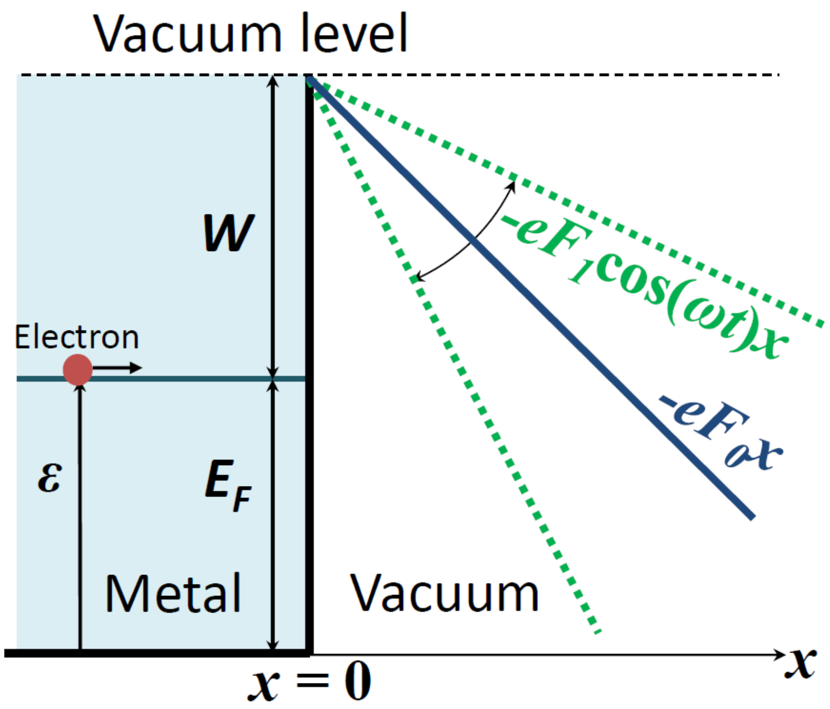
$$\epsilon_g(\omega) = 1 - \omega_g^2/[\omega(\omega + i\gamma_g)]$$




By increasing the driving field to **field emission or space-charge-limited regime**, $\gamma_g$ can be significantly reduced for CTP via tunneling

# Ultrafast Electron Emission



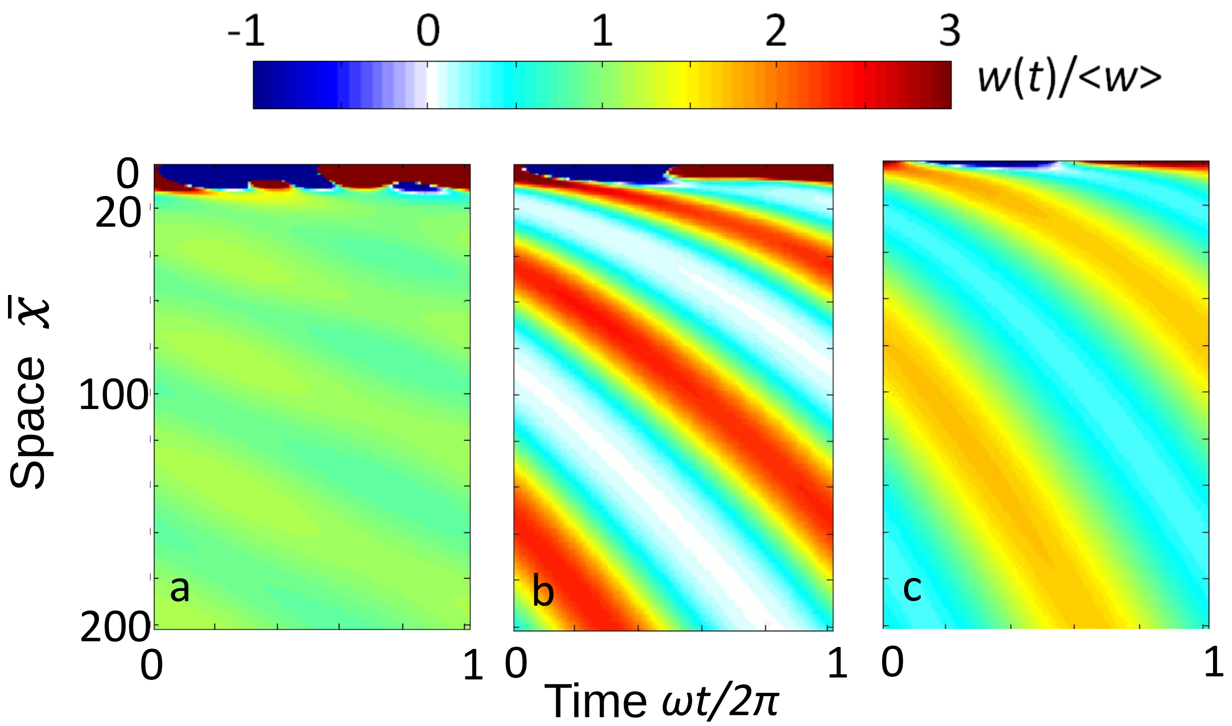




We have discovered an exact solution* to the time-dependent Schrödinger equation, for arbitrary values of dc bias, laser field and frequency, and metal work function and Fermi level.

*Peng Zhang and Y. Y. Lau, Sci. Rep., 6, 19894 (2016).

# Time-Dependent Emission Current

Laser intensity $I = 1.33 \times 10^{11}$ W/cm$^2$ **($F_1$ = 1V/nm)**




$F_0$ = **1 V/nm** $F_0$ = **5 V/nm** $F_0$ = **10 V/nm**

Laser wavelength
$\lambda = 800$ nm

Work function
$W = 5.1$ eV

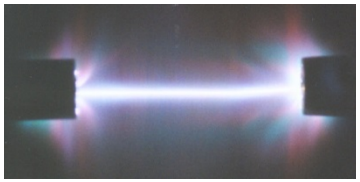
Fermi energy
$E_F = 5.53$ eV

Intense current modulation may be possible even with a **low intensity laser**, by merely increasing the dc bias.

# Current Crowding and Contact Resistance

Electrical contact is everywhere …

**Wire-array Z pinches**

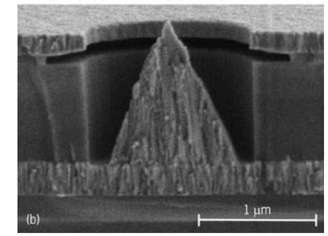


Z-pinch @ UM, Sandia

**High power microwave (HPM) sources**

UM/ L-3-Titan relativistic magnetron

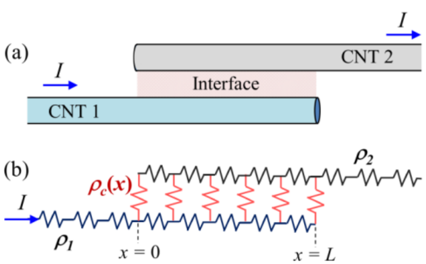
**Field emitters**

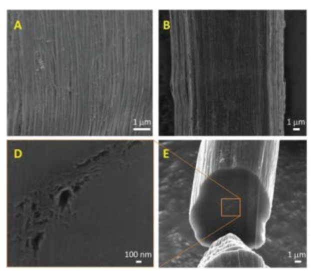



http://accessscience.com

In nanoscale, making good contacts remains the major challenge

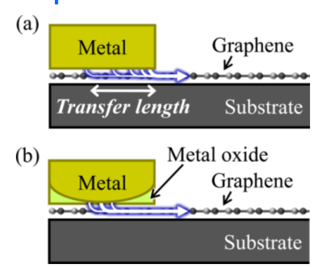
Contact resistance between CNTs/Nanowires




Science, 339, pp. 182-186 (2013)

Graphene contacts




Nouchi and Tanigaki, APL, **105**, 033112 (2014)

## Classical models

Zhang and Lau, *JAP*, **108**, 044914 (2010).
Zhang, Hung, and Lau, *JPD: AP*, **46**, 065502 (2013).
Zhang, and Lau, *APL* **104**, 204102 (2014).
Zhang, Gu, Lau, and Fainman, IEEE JQE, 52, 2000207 (2016).

## Ballistic/quantum models

Zhang, and Hung, *JAP*, **115**, 204908 (2014).
Solomon, IEEE EDL, 32(3), 246 (2011).
Grosse, et al, Nat. Nanotech. 6 287 (2011).
Xia, et al, Nat. Nanotech. 6, 179 (2011).

**The transition between these regimes remains unclear**

# Future Research

DoE Whitepaper on the Frontiers of Plasma Science (July 2015)

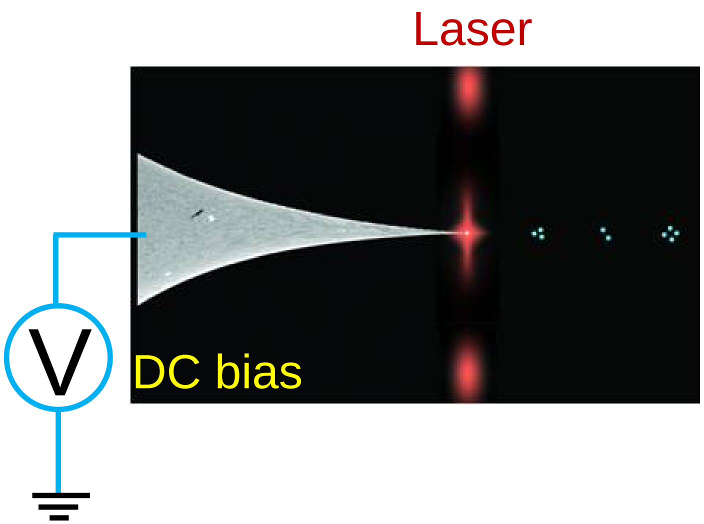
**Ultrafast and nanoscale interfacial charge transport and its interaction with electromagnetic waves**

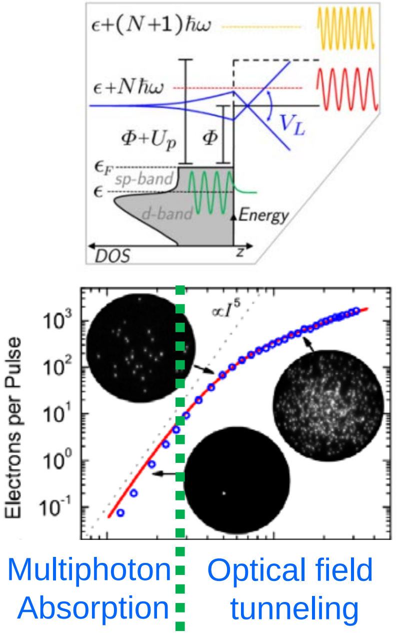
Peng Zhang* (U Michigan), John Luginsland (AFOSR), Y. Y. Lau (U Michigan), John Booske (U Wisconsin), Ron Gilgenbach (U Michigan), Kevin Jensen (NRL), Marty Peckerar (U Maryland), Don Shiffler and Steven Fairchild (AFRL), John Verboncoeur (Michigan State), Ricky Ang (Singapore University of Technology and Desgin), Avi Gover (Tel Aviv University), Agust Valfells (Reykjavik University, Iceland)

*Corresponding Author: umpeng@umich.edu

https://www.orau.gov/plasmawkshps2015/whitepapers.htm

# Ultrafast Electron Emission and Modulation

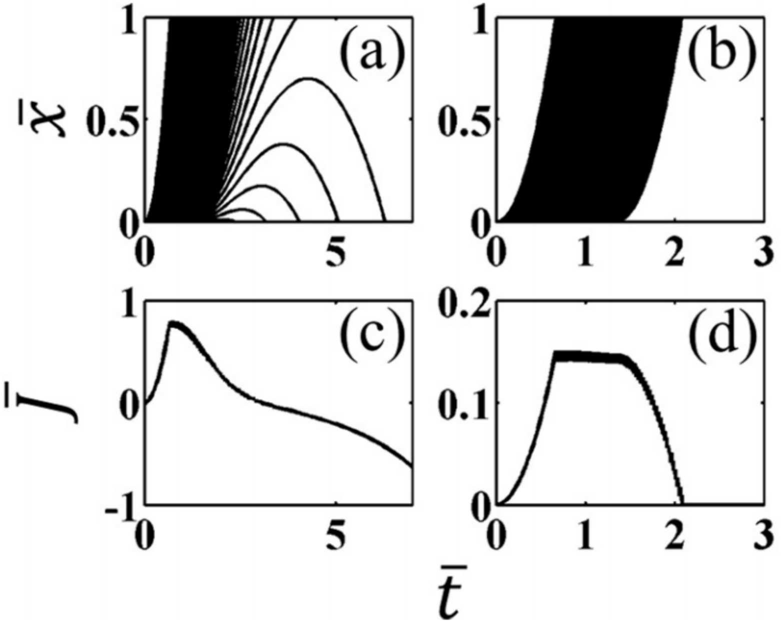


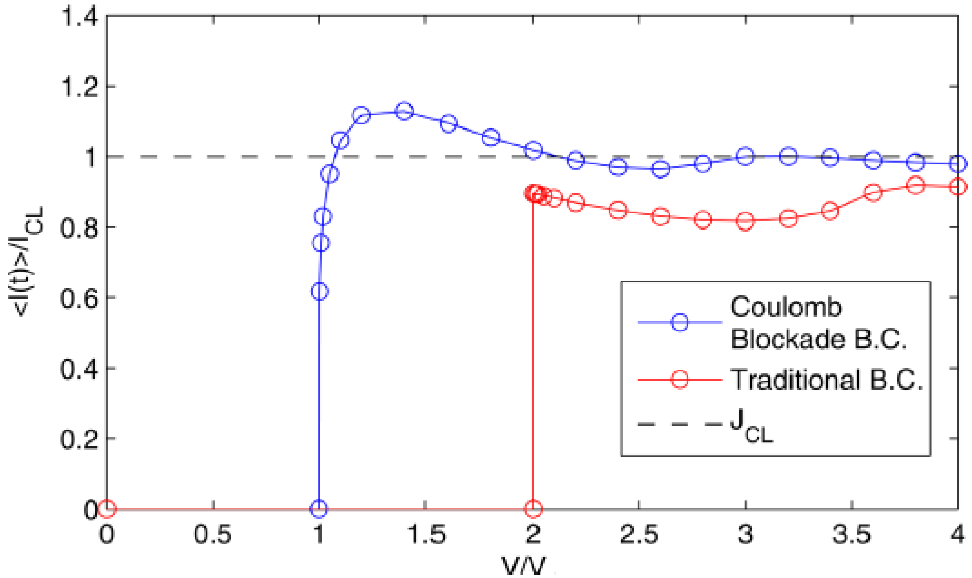




Bormann et al, PRL 105, 147601 (2010)

- ✓ General model for transition between different emission
- ✓ Charge redistribution and thermalization
- ✓ Field enhancement, space charge
- ✓ Multi-frequency laser, few cycle laser, new materials
- ✓ Optical phase modulation

# Transient time model in a gap



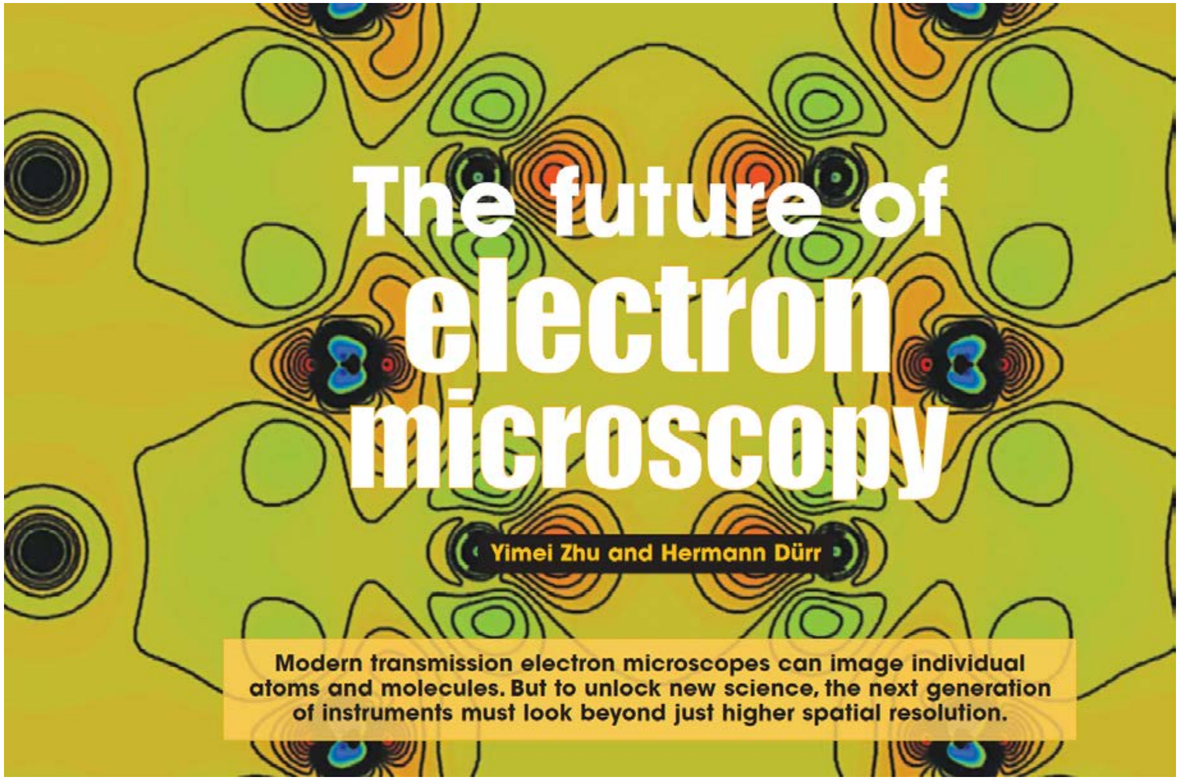




Zhu and Ang, APL 98, 051502 (2011)
Zhu, Zhang, Valfells, Ang, and Lau, PRL 110, 265007 (2013).
Liu, Zhang, Chen, and Ang, PoP, 22, 084504 (2015); PRST-AB, 18, 123402 (2015).

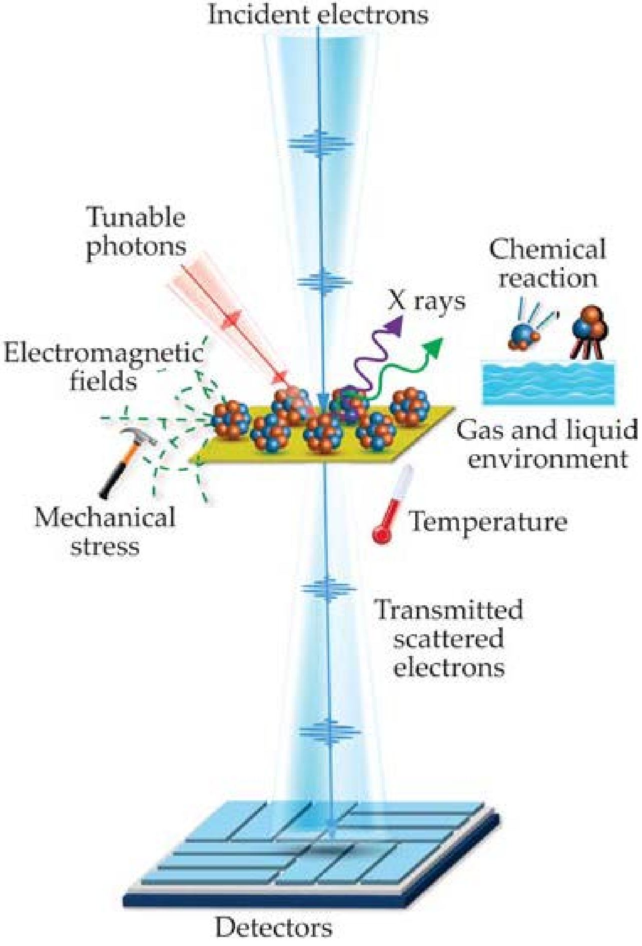
Griswold, Fisch, and Wurtele, PoP 17, 114503 (2010).
Griswold, Fisch, and Wurtele, PoP 19, 024502 (2012).
Griswold, and Fisch, PoP 23, 014502 (2016).

✓Space charge under ultrafast condition

These studies could lead to ….



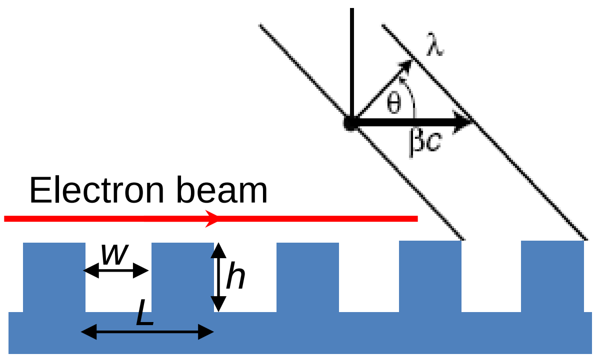

Physics Today **68**(4), 32 (2015)

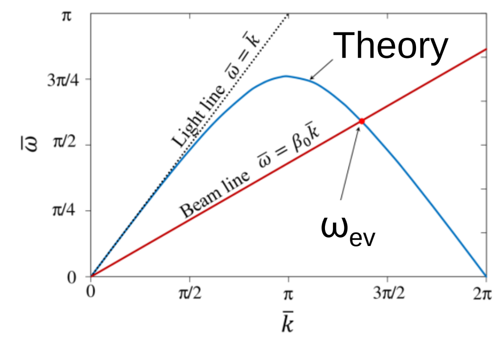


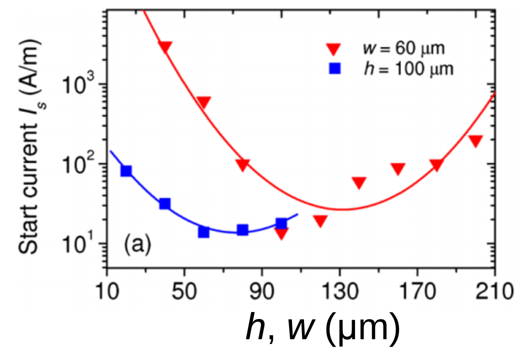

*in situ* electron microscopy for 3D imaging and spectroscopy in real space, momentum space, energy space, time space, and external parameter space.

# Beam Interaction with Novel Nanostructures

Smith-Purcell effect shows promise for coherent terahertz radiation generation.




Zhang, Ang, and Gover, PRST-AB, 18, 020702 (2015).

✓Radiation from novel materials (graphene) & structures (metamaterials & photonic crystals) requires significant improvement on the efficiency.

✓Origin of current minimum?
✓The lowest limit in wavelength?

# Summary

**Frontier Research Topics:**

1. **Nanoscale charge transport**
2. **Ultrafast electron emission and transport**
3. **Beam interaction with plasmonics and meta-materials**

- They are multidisciplinary, encompassing plasma sciences, nano-optoelectronics and nonlinear optics, with applications far beyond: single-molecule sensing, molecule electronics, resistive switching, carbon nanotube and graphene based electronics.