# Surface and Nano Sciences Lab

(www.phys.sinica.edu.tw/~nano/)

鄭天佐(1990)
Tien T. Tsong

張嘉升(1991)
C.S. Chang

黃英碩(1994)
I.S. Hwang

蘇維彬(2001)
W.B. Su

胡恩德(2010)
A.D. Hwu

魏金明(1991)
C.M. Wei

Surface dynamics, epitaxial growth, atom manipulation
bio-imaging

**FIM, SPM, TEM**

Calculations and simulations

**Theoretic work**

**UHV TEM + STM**

Size-, shape-, and site-specific properties of nanomatrerials

**Nanoscience**

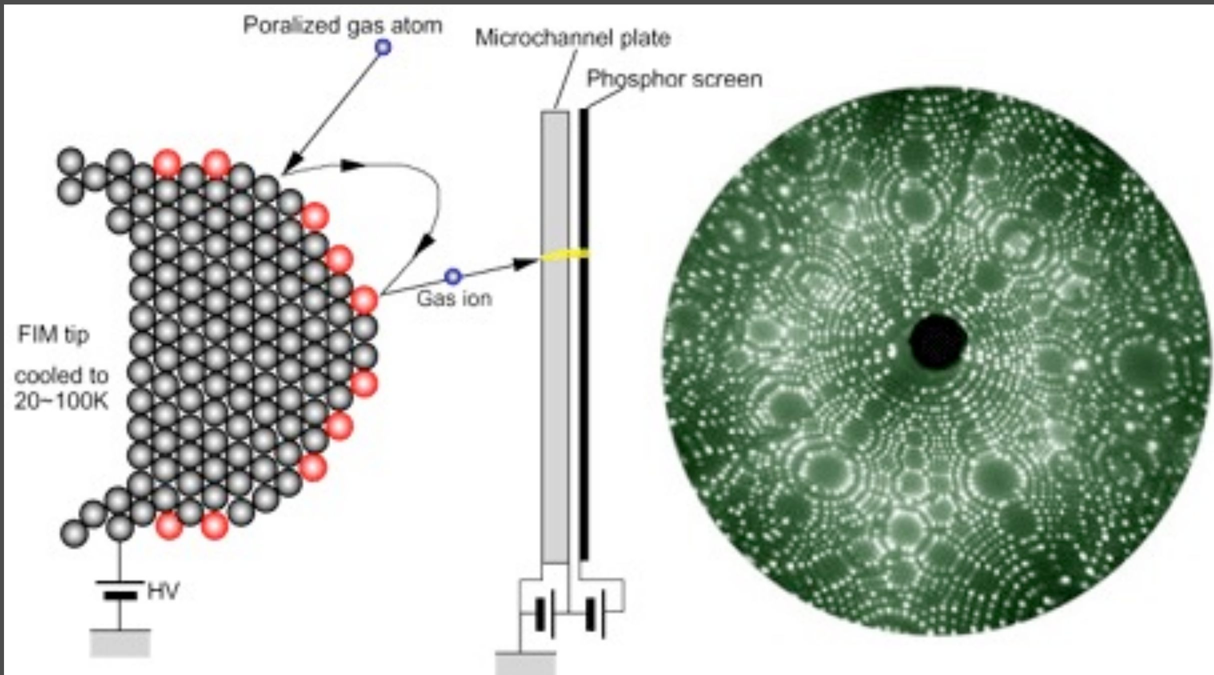
**LT STM + magnet**

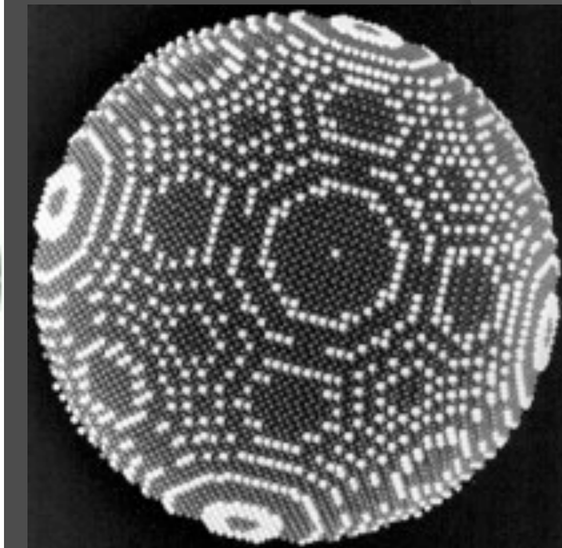
Single spin detection, quantum phenomena in nanostructures

**Nanotechnology**

New tools, new instruments, new methods

# Field Ion Microscopy

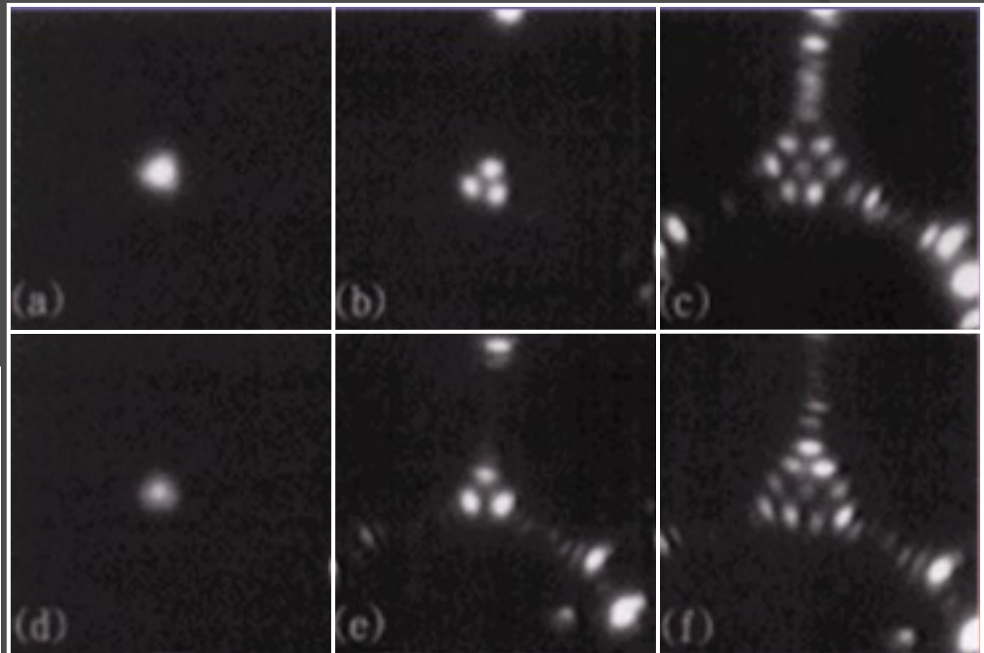


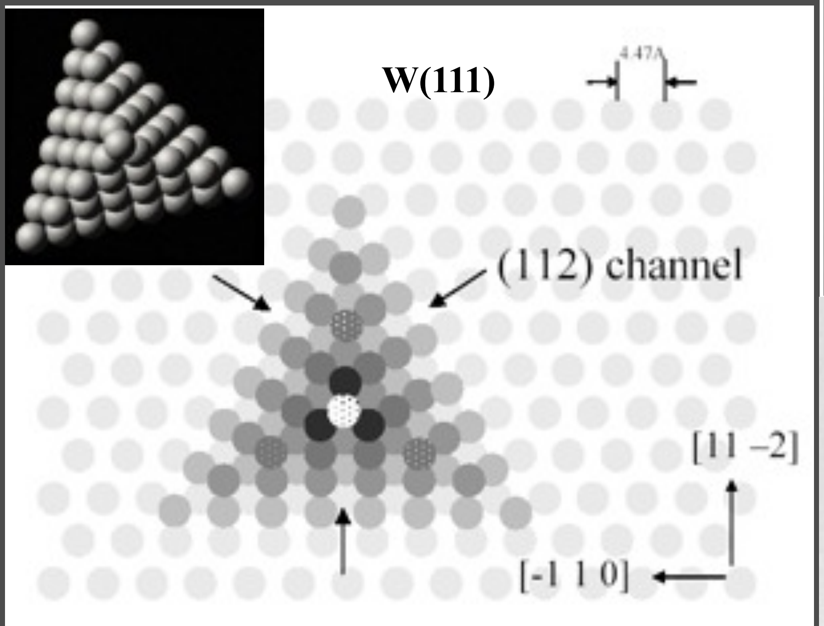



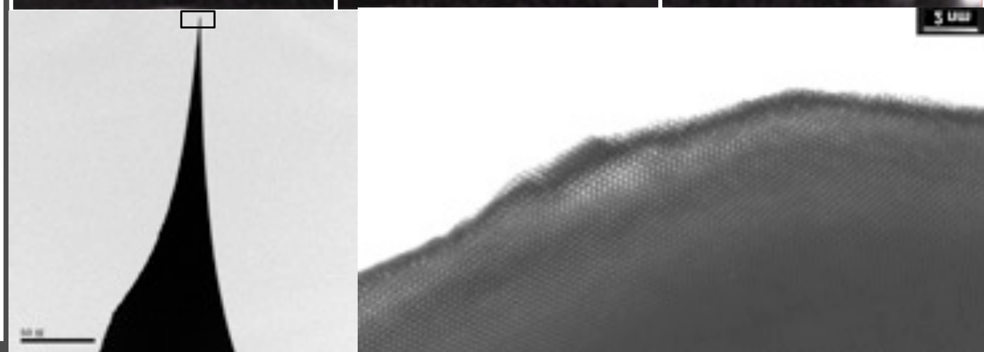
The image gas atoms in the vicinity of the specimen are polarized because of the high field and then attracted to the apex region of the specimen. After a series of collisions with the specimen during which the image gas atoms lose part of their kinetic energy, these image gas atoms become thermally accommodated to the cryogenic temperature of the specimen. If the field is sufficiently high, these image gas atoms are field ionized by a quantum-mechanical tunneling process. The ions produced are then radially repelled from the surface of the specimen towards the microchannel plate and screen assembly. A microchannel plate image intensifier positioned immediately in front of the phosphor screen produces between $10^3$ and $10^4$ electrons for each input ion. These electrons are accelerated towards the phosphor screen where they produce a visible image. The field-ion microscope was invented by Erwin Müller in 1951 at Pennsylvania State University.

# Single atom tip

1) STM probing
2) Coherent $e^-$ beam
3) Point ion source



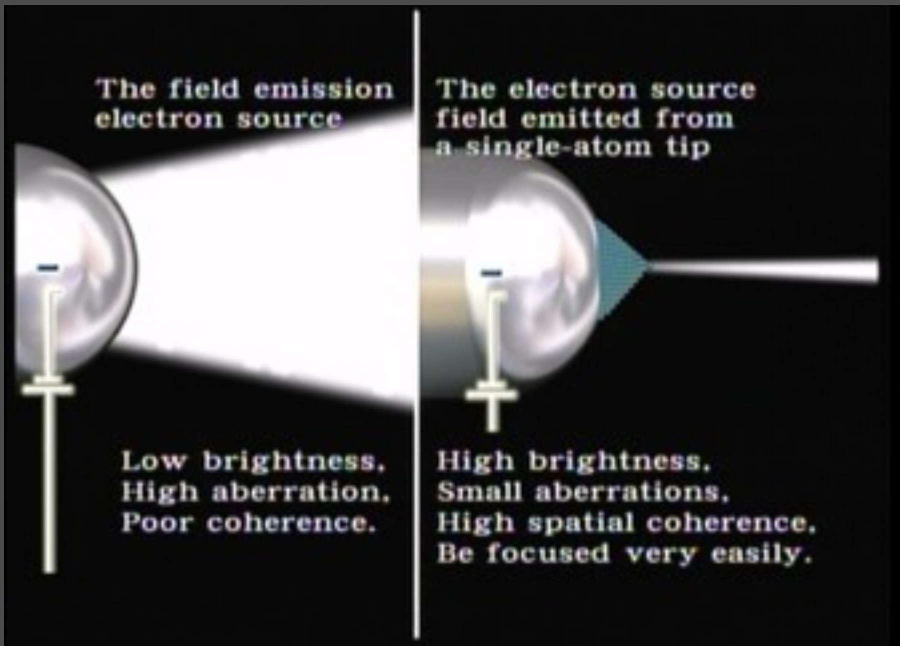
# E-beam and ion beam sources

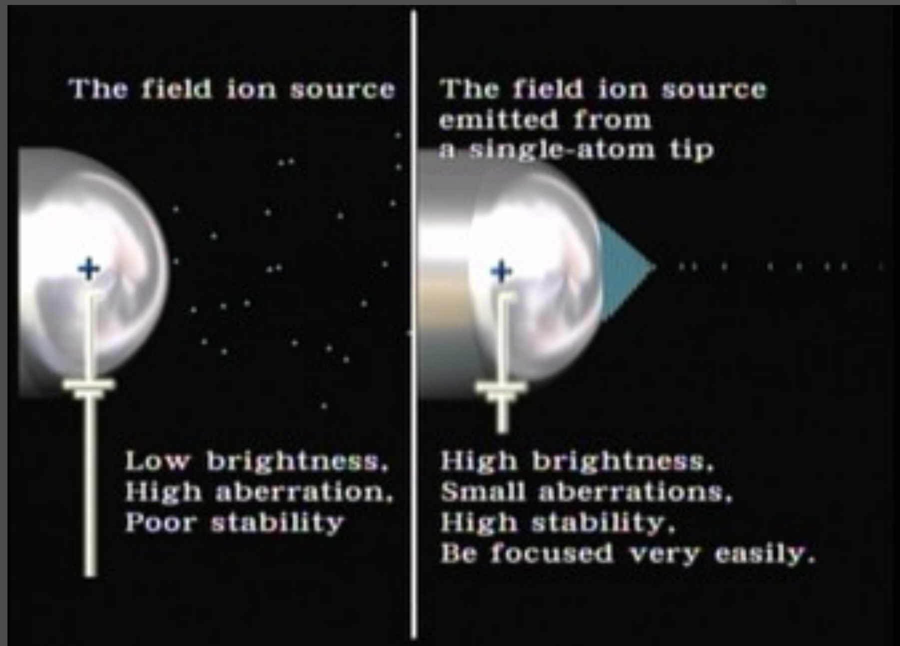
Traditional

Ideal electron point source

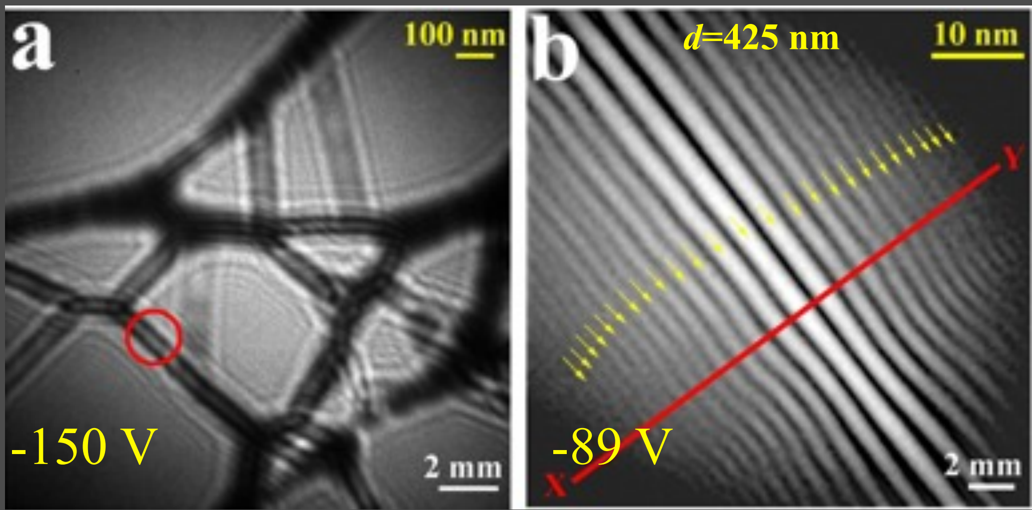
Traditional

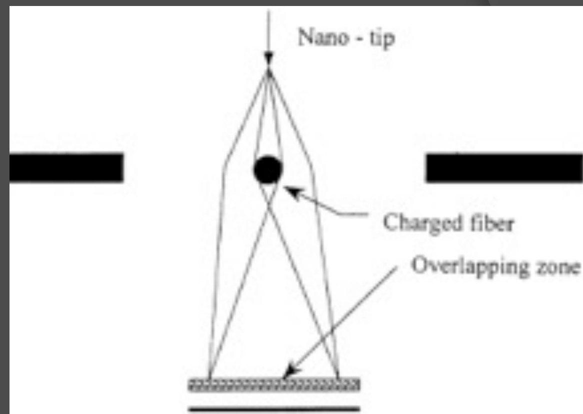
Ideal ion point source



# High degree of spatial coherence



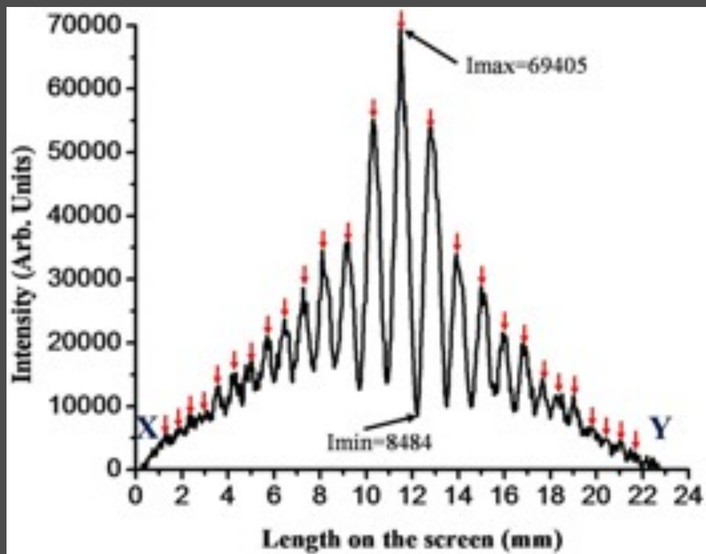

**Electron Biprism**

SWNT bundle can act as a nanoprism, which splits the wavefront of an incoming electron wave into two coherent partial waves, which are deflected by the electric fields around the nanoprism in opposite directions and meet on the screen.

Visibility

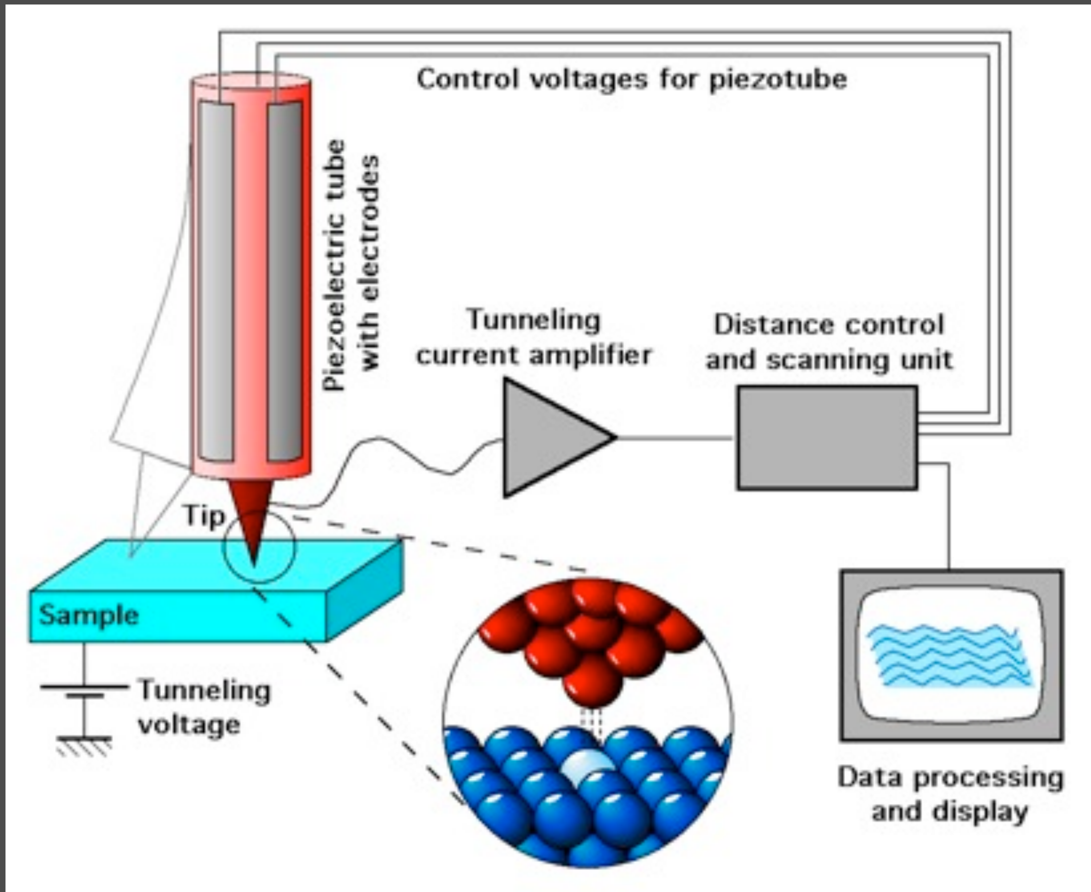
$$V = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})}$$

$= 0.78$




Nanotechnology **20**, 115401 (2009)

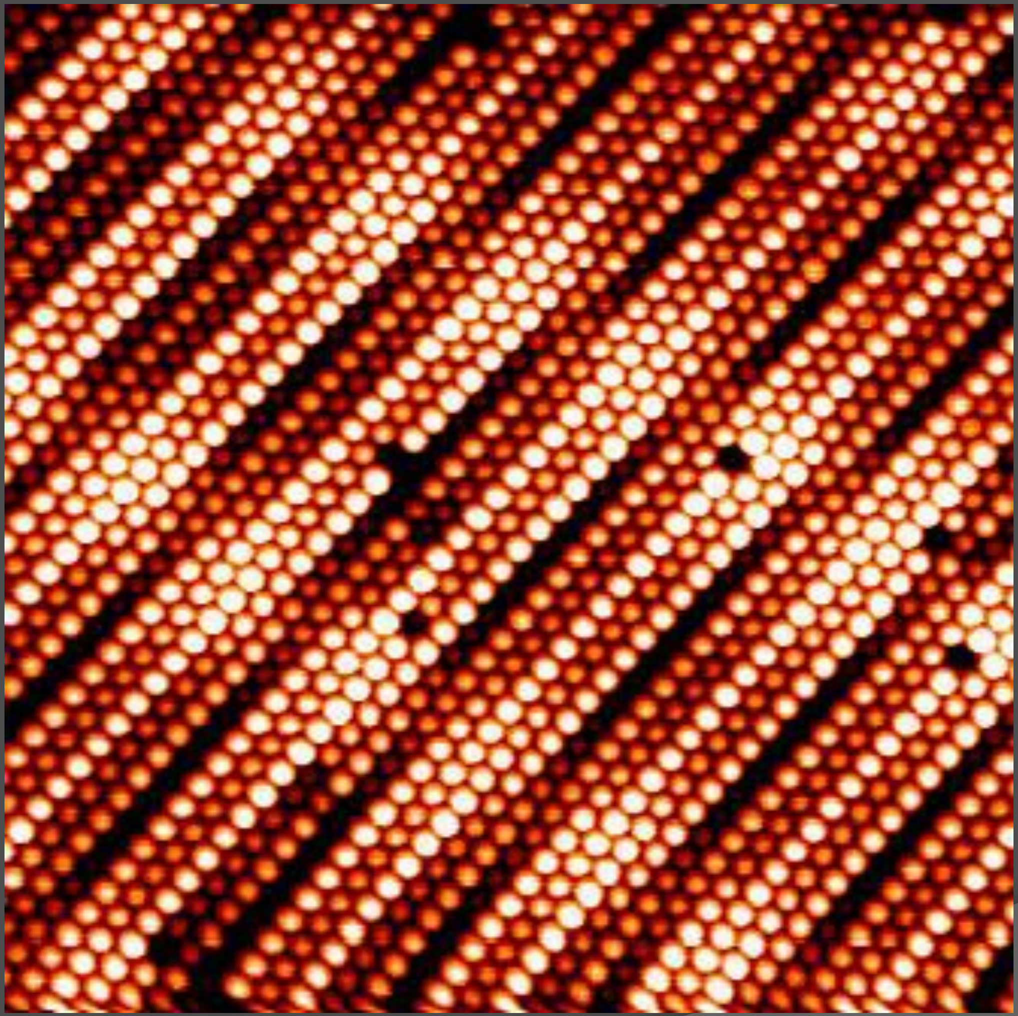
# Scanning Tunneling Microscopy




References:


1. G. Binnig, H. Rohrer, C. Gerber, and Weibel, Phys. Rev. Lett. **49**, 57 (1982); and ibid **50**, 120 (1983).
2. J. Chen, *Introduction to Scanning Tunneling Microscopy*, New York, Oxford Univ. Press (1993).

# Pt(001) reconstructed Surface



Surface Science **306**, 10 (1994)

# Surface and interface properties of ultrathin metal films on Si and Cu substrates

Jason Chang, Wei-Bin Su, and Tien T. Tsong

Institute of Physics, Academia Sinica

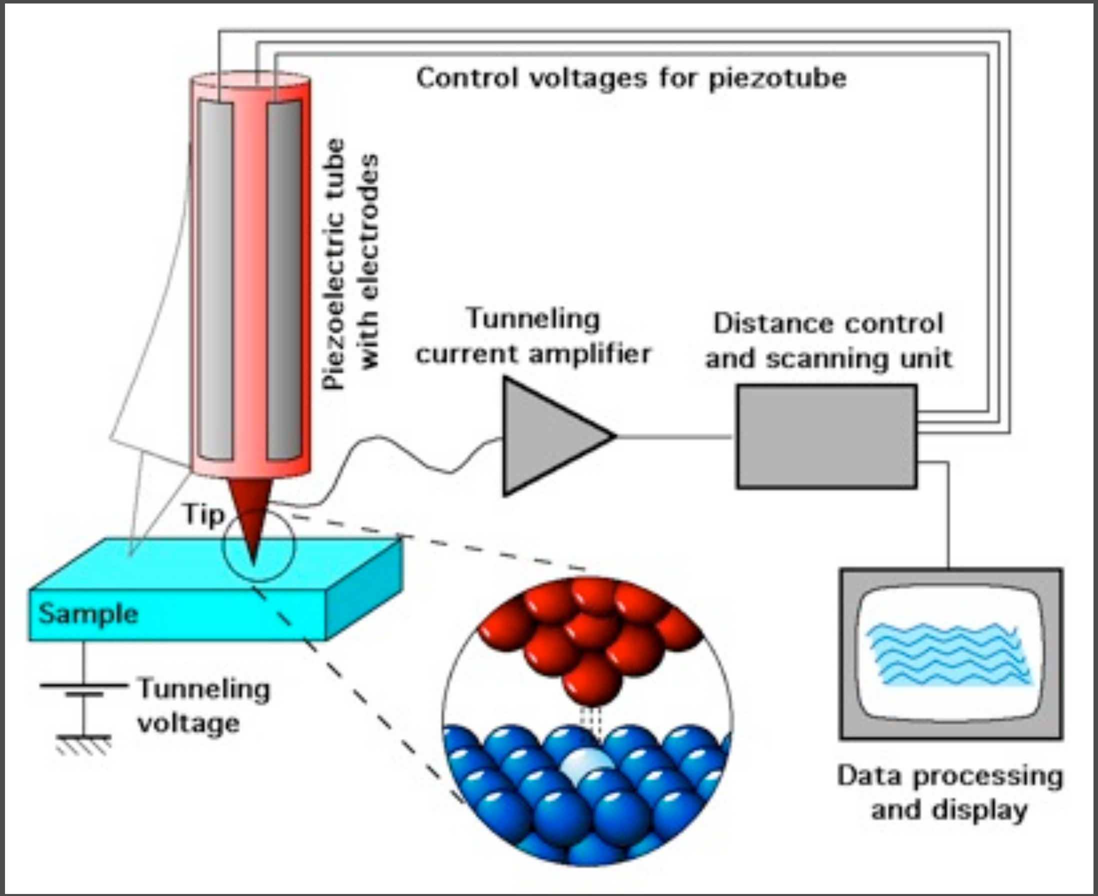
Taipei, Taiwan

Supported by the National Program for Nanoscience and Technology, NSC, Taiwan

# Outline

- Quantum well states in ultrathin Pb films
  - Manifestation of interfacial potential
  - Effect of image potential
- Gundlach osillations in STM configuration
  - Work function measurements
- Transmission resonance through thin films
  - Determination of film thickness

# Scanning Tunneling Microscopy

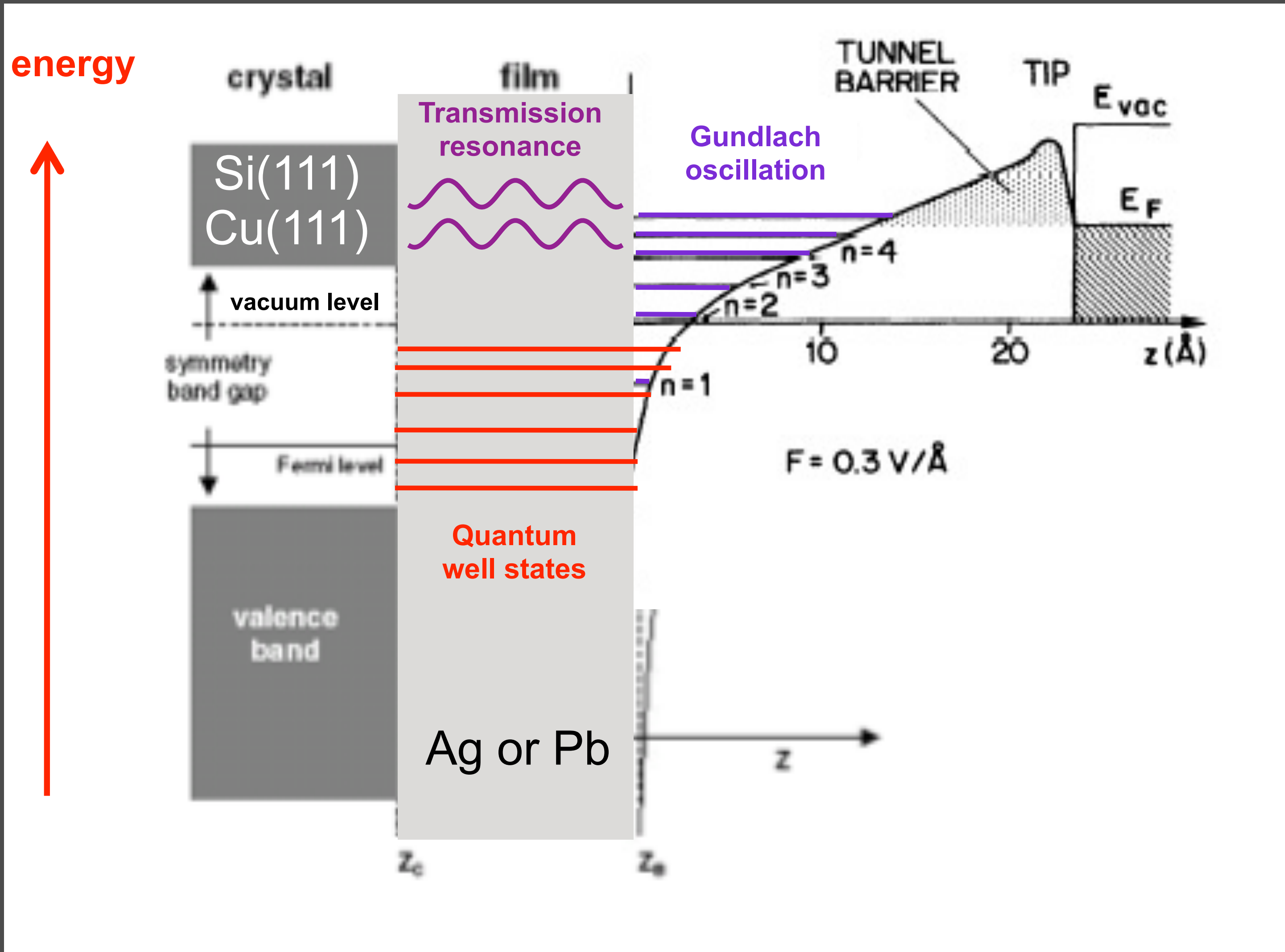




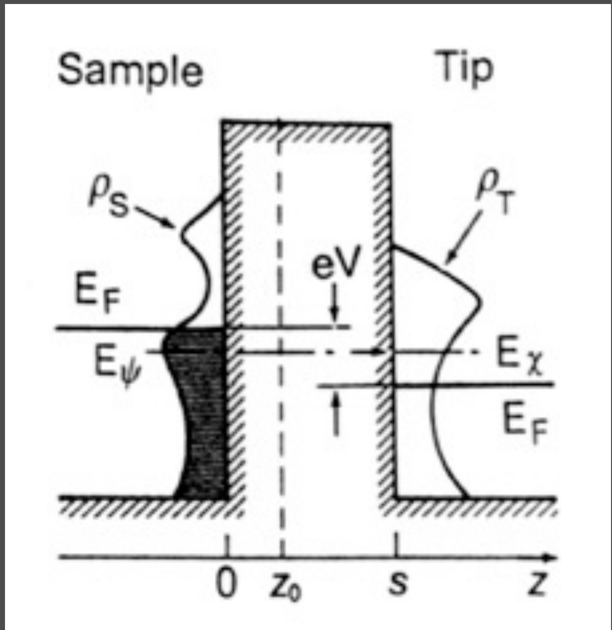
References:

1. G. Binnig, H. Rohrer, C. Gerber, and Weibel, Phys. Rev. Lett. **49**, 57 (1982); and ibid **50**, 120 (1983).
2. J. Chen, *Introduction to Scanning Tunneling Microscopy*, New York, Oxford Univ. Press (1993).

# Various quantum phenomena

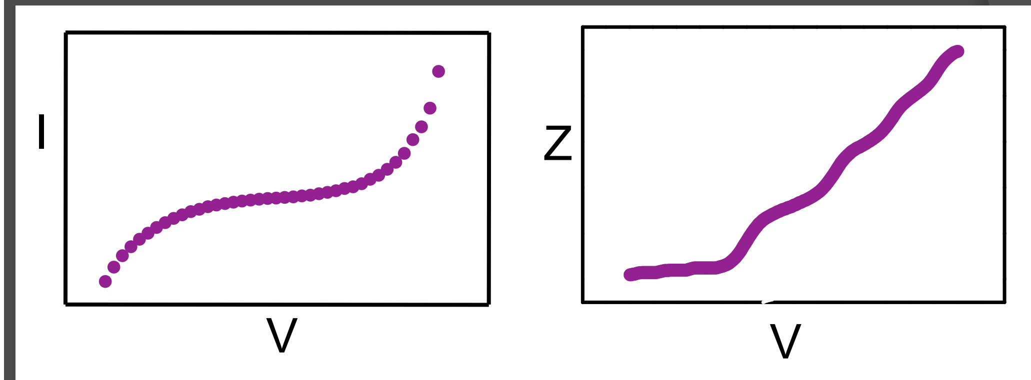


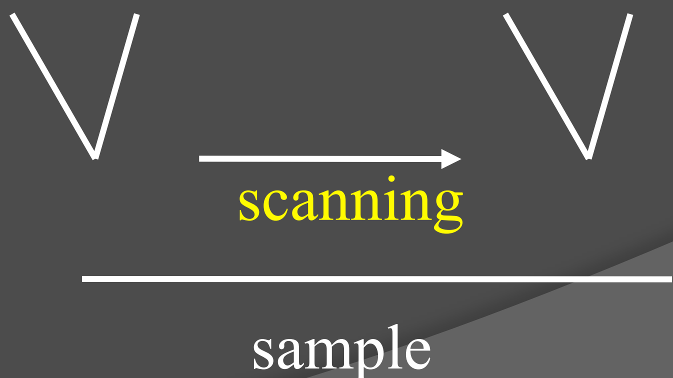
# Scanning Tunneling Spectroscopy




(feedback off)
I-V spectrum

(feedback on)
Z-V spectrum

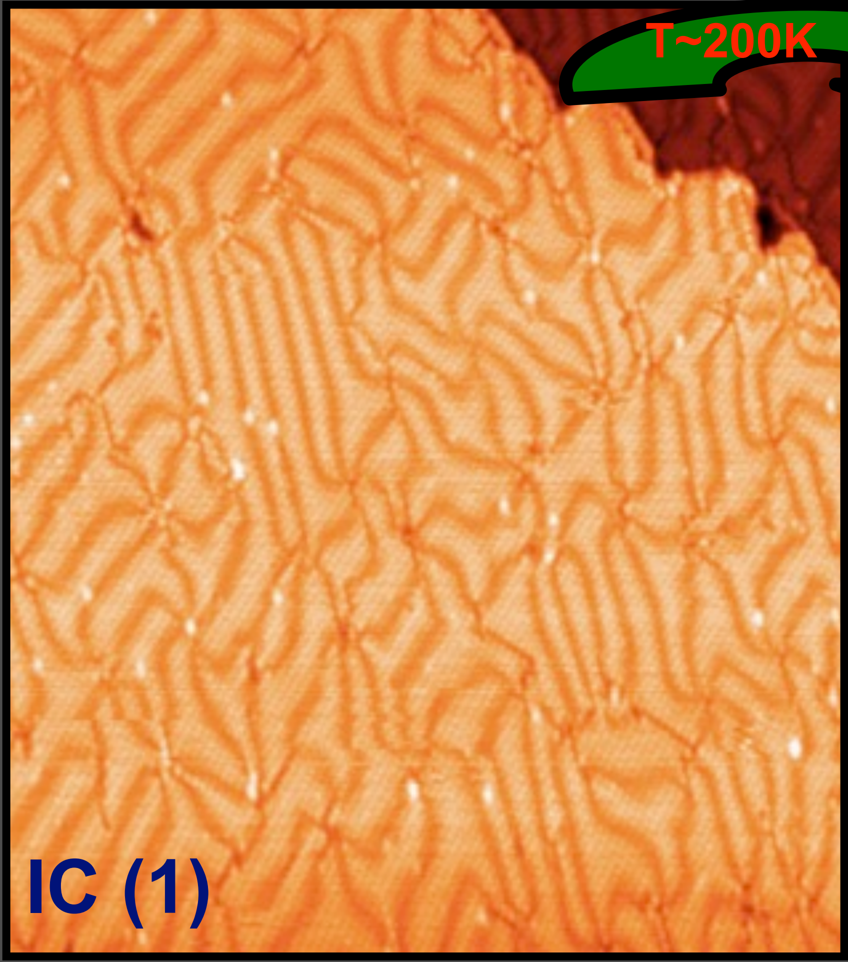


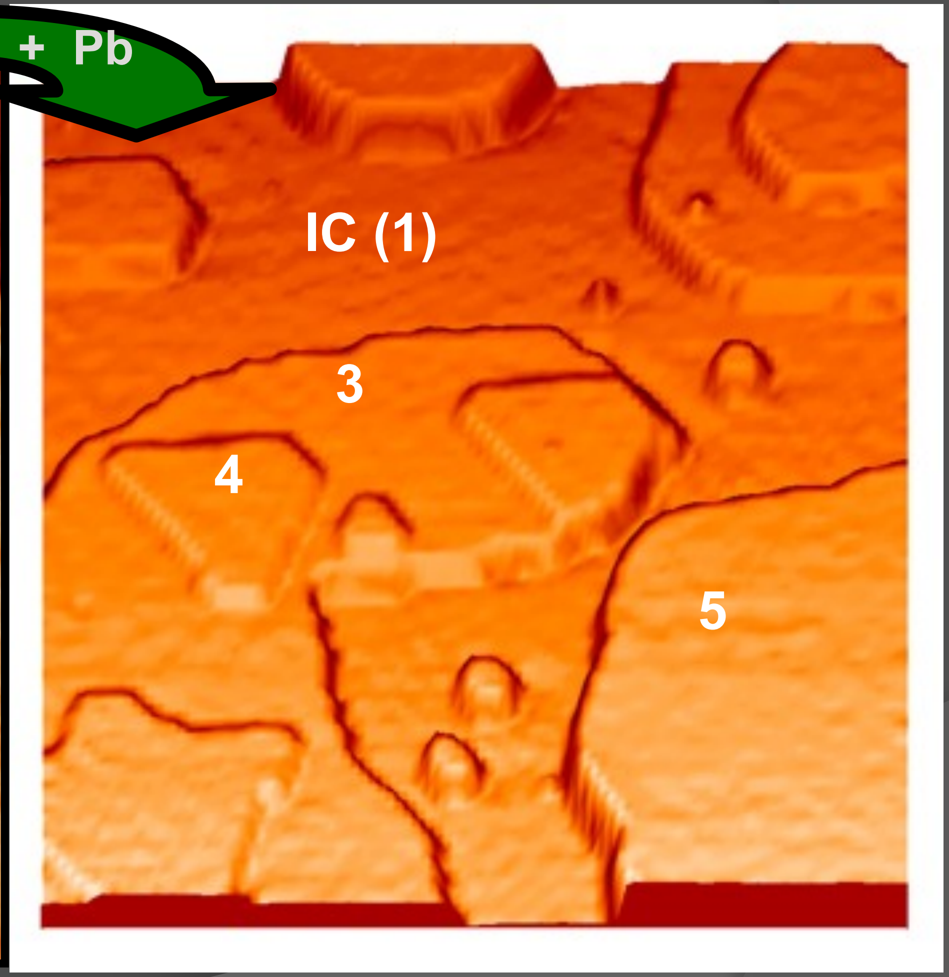




$$I \propto \int_0^{eV} \rho_s(E_F\text{-}eV+\varepsilon)\ \rho_T(E_F+\varepsilon)d\ \varepsilon$$

$\rho_T$ is constant $\Rightarrow dI/dV \propto \rho_s(E_F\text{-}eV)$

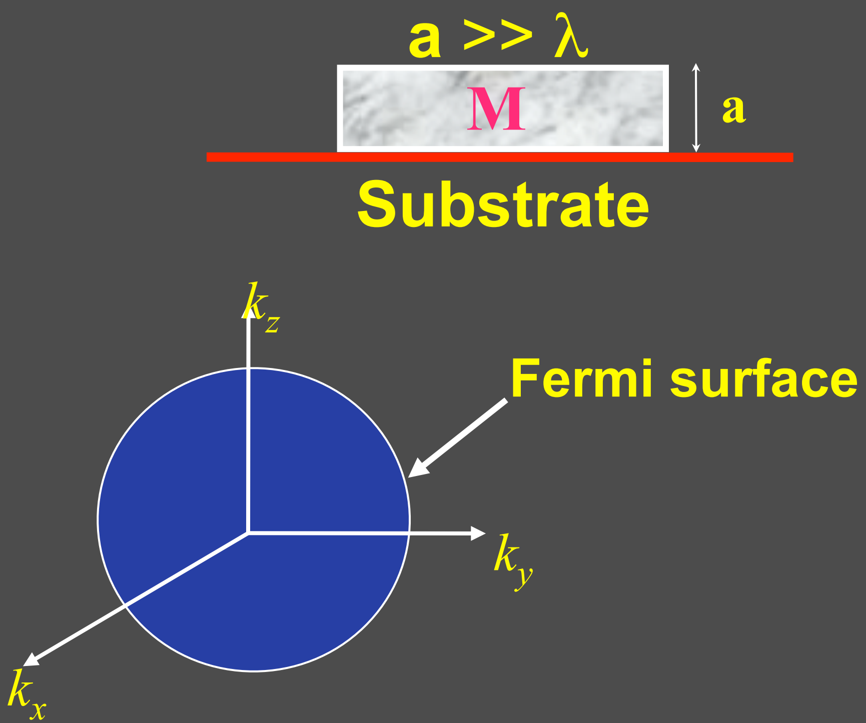
# Pb islands on the IC Pb/Si(111)

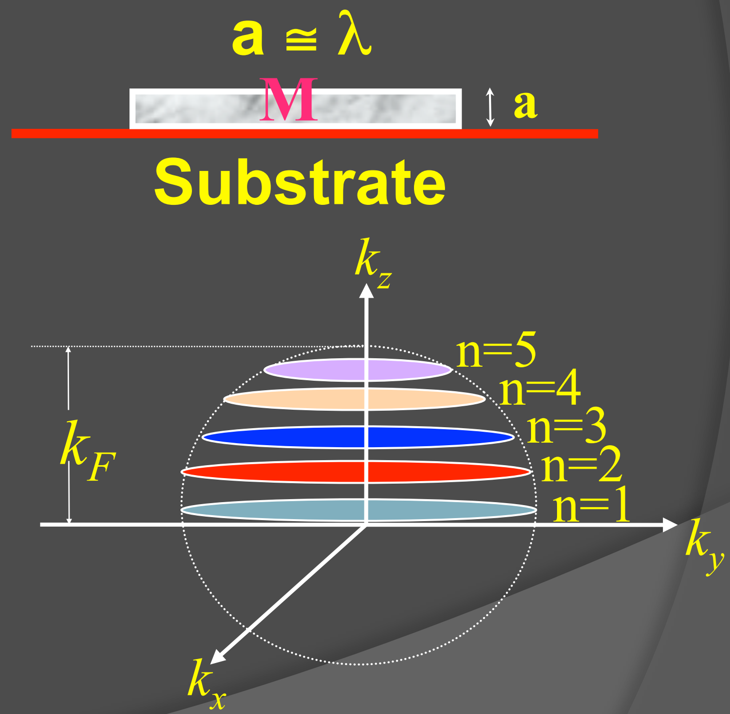


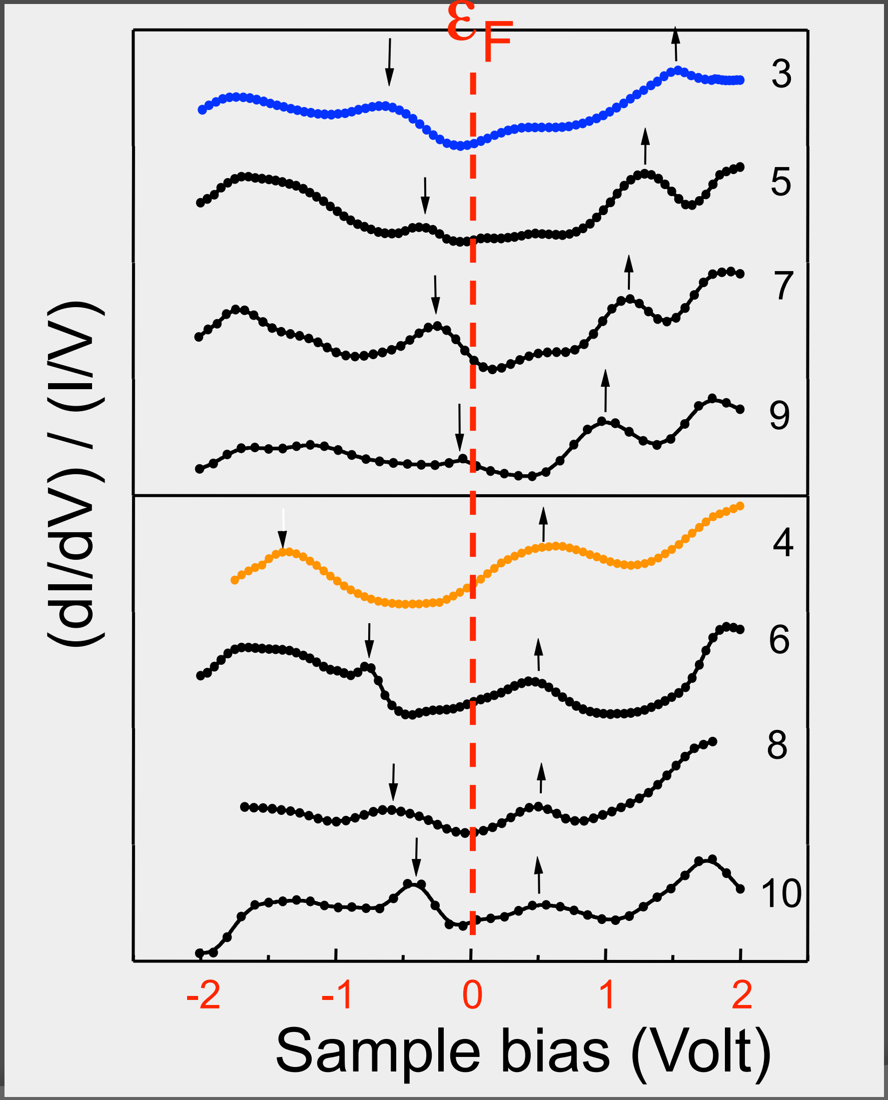
# Quantum size effect

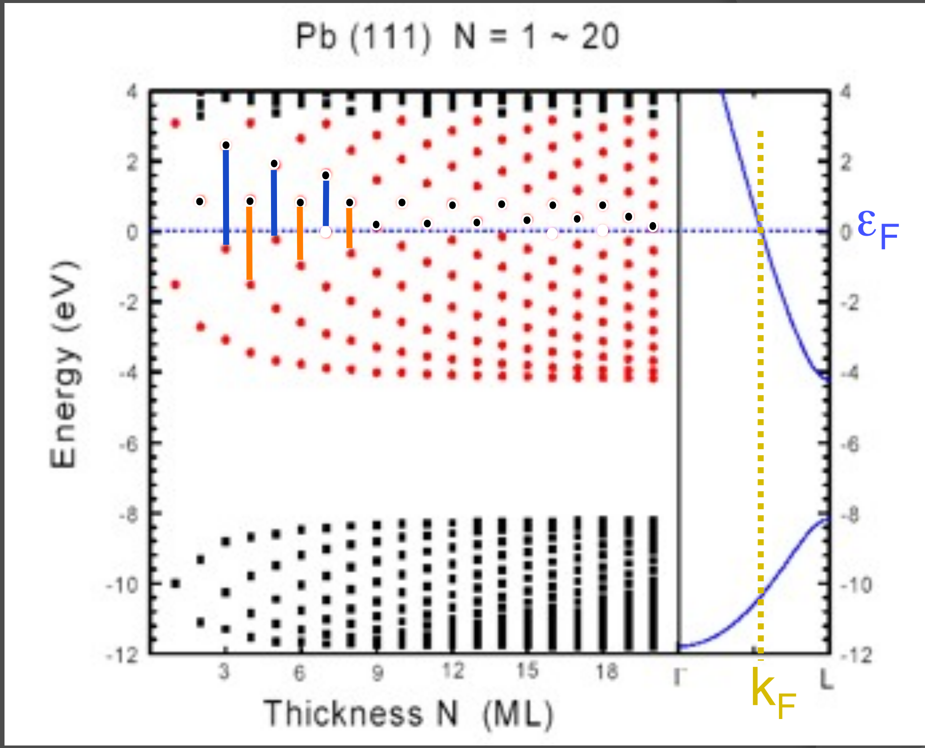
λ = de Broglie wavelength of electron
**a** = thickness of metal film



# Spectra for Pb Films



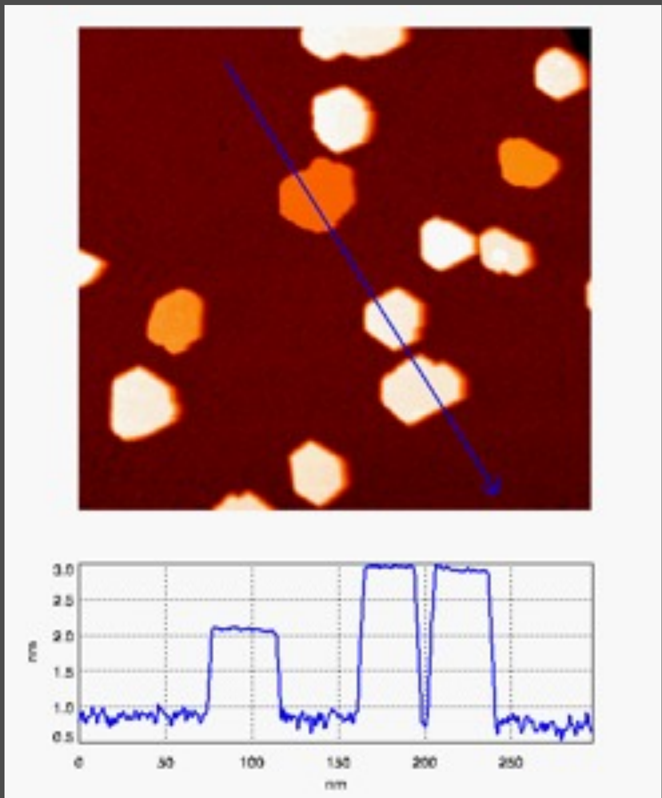



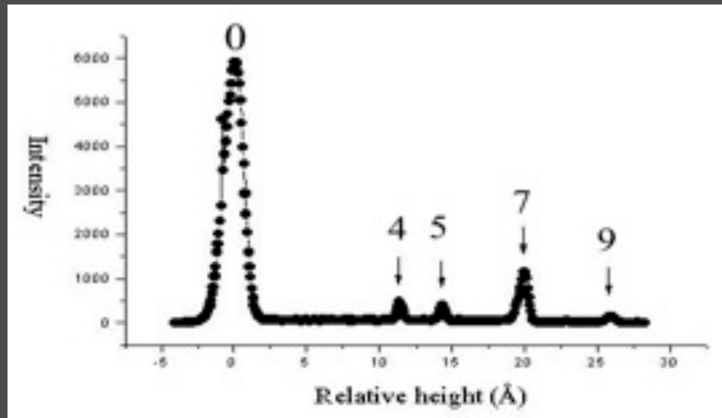

C.M. Wei and M.Y. Chou

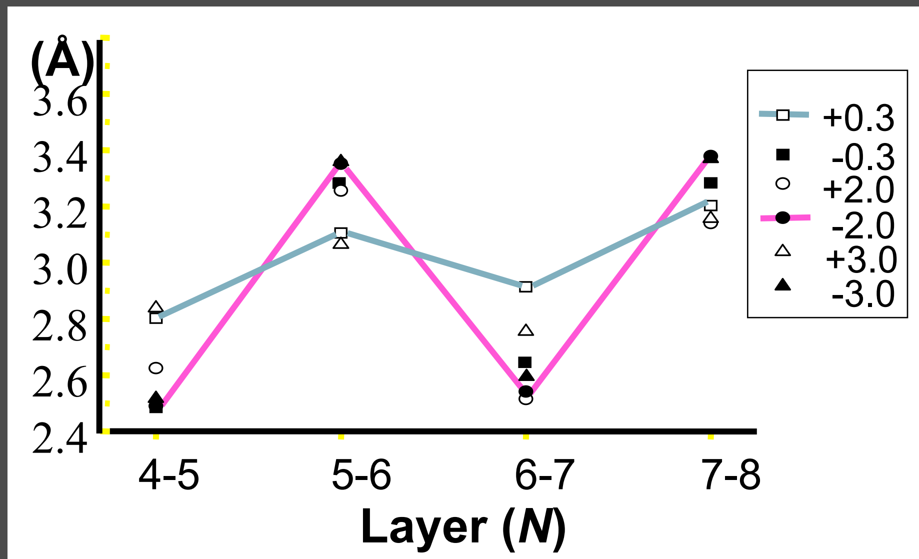
$d_0$ = 2.85 Å $\lambda_F$ = 3.94 Å

$2d_0 \approx 3(\lambda_F/2)$

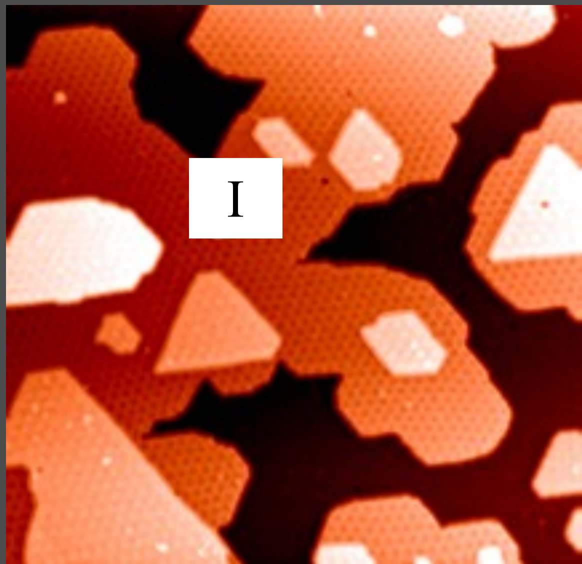
# Apparent island heights

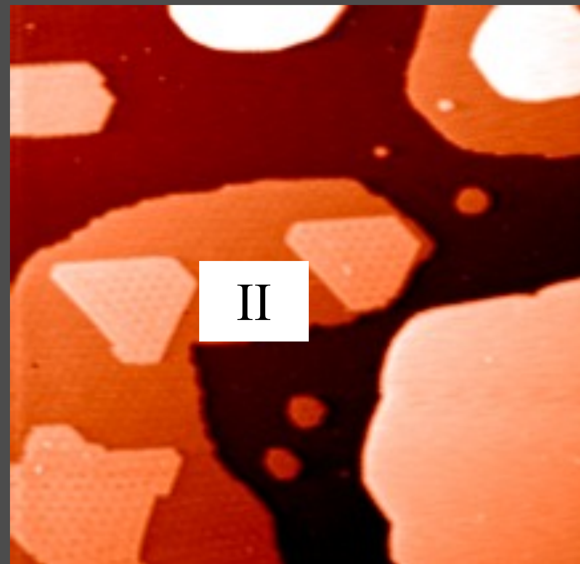


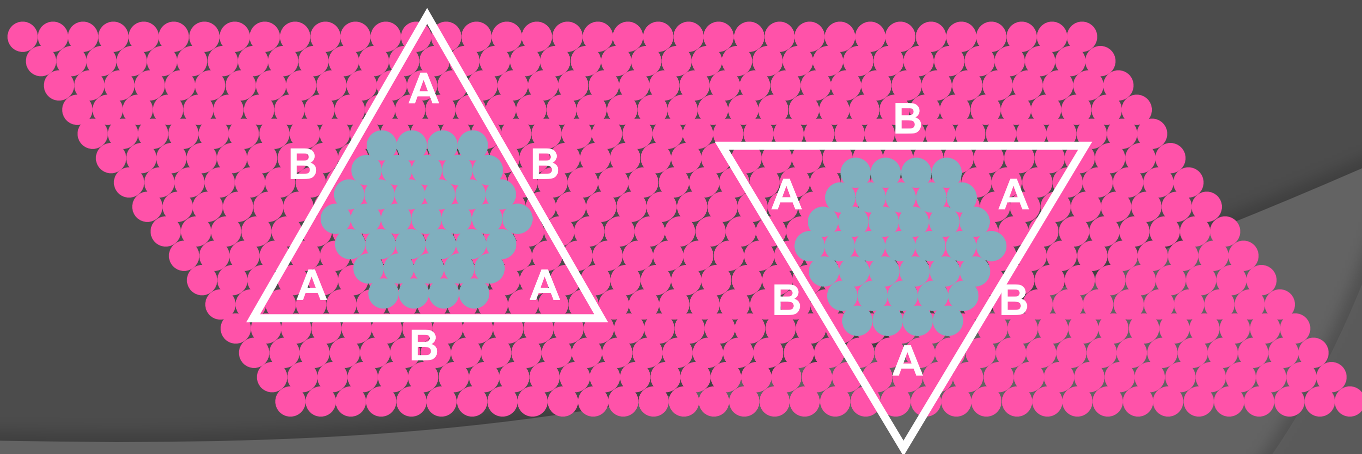



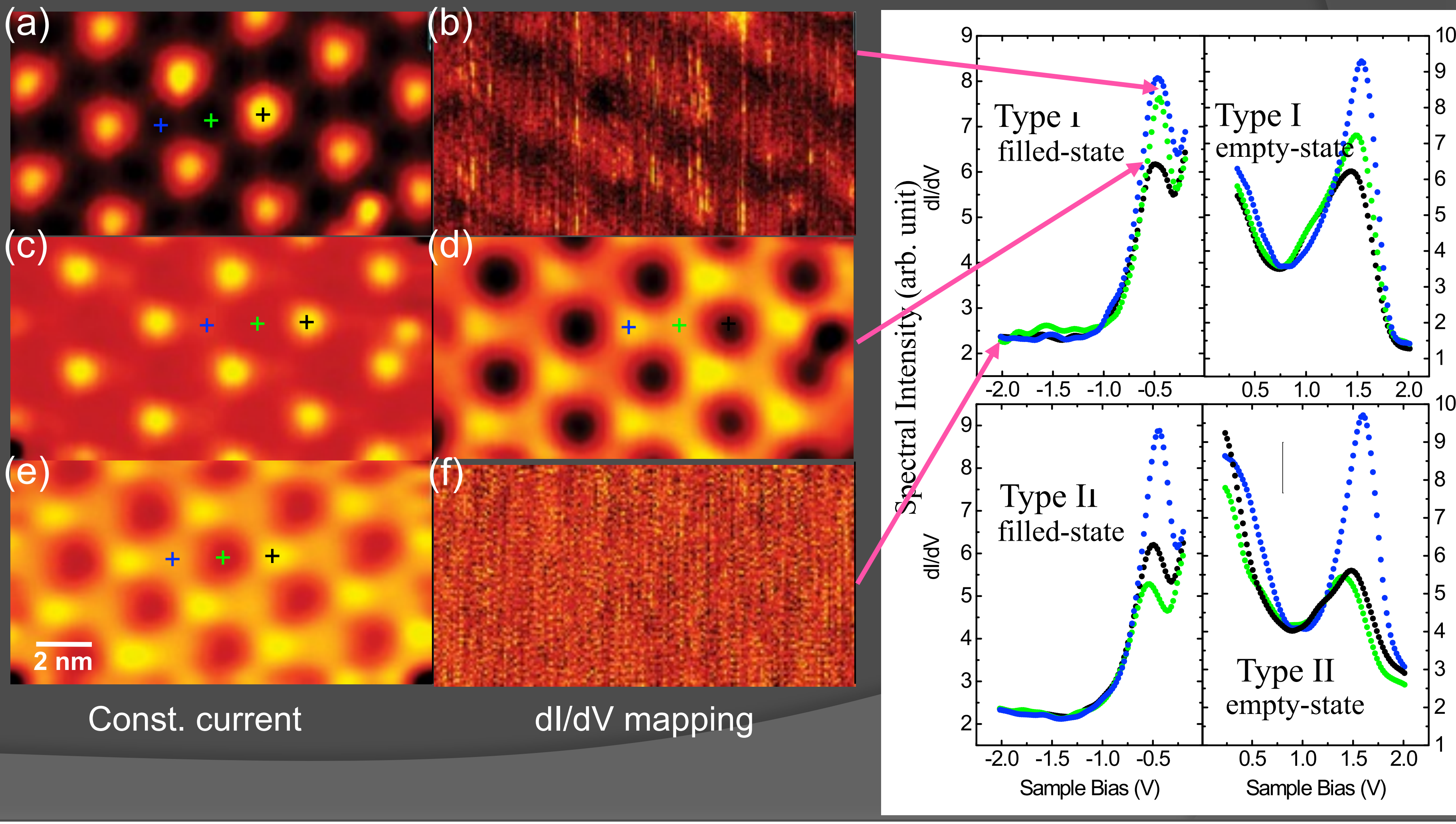
# Difference in layer stacking



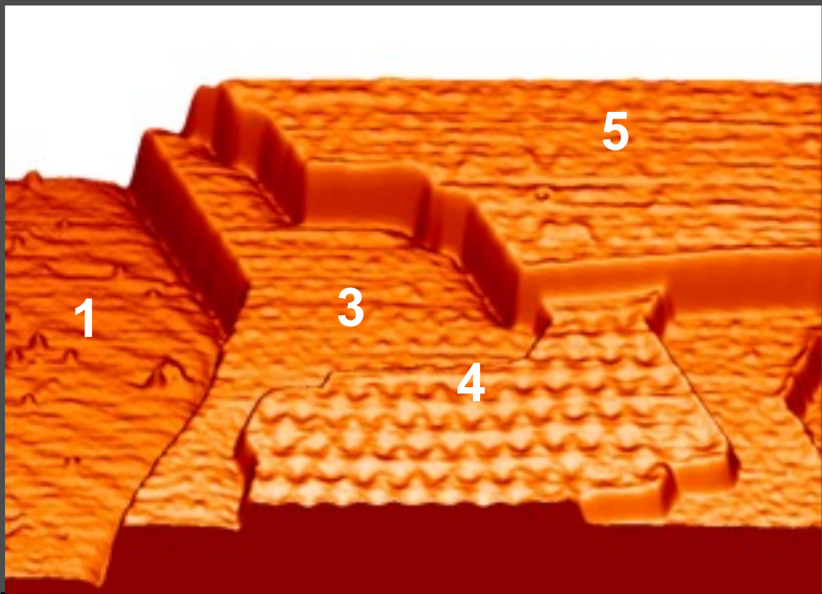



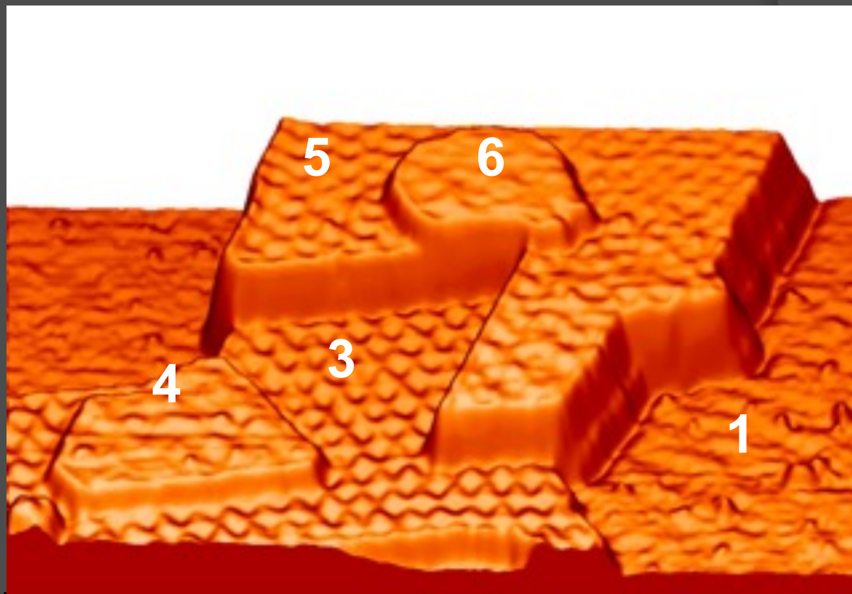
# Characteristics of Pb islands---Bias-dependent imaging contrast



# Characteristics of Pb island: oscillatory and complementary contrast



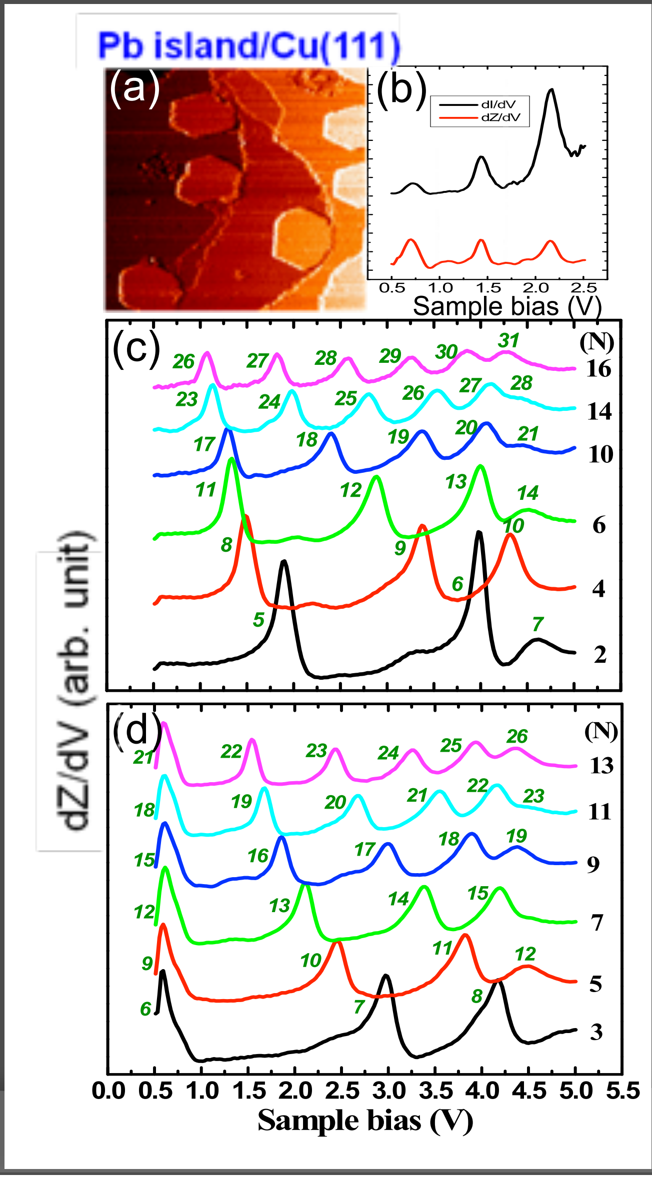

Type II




Type I

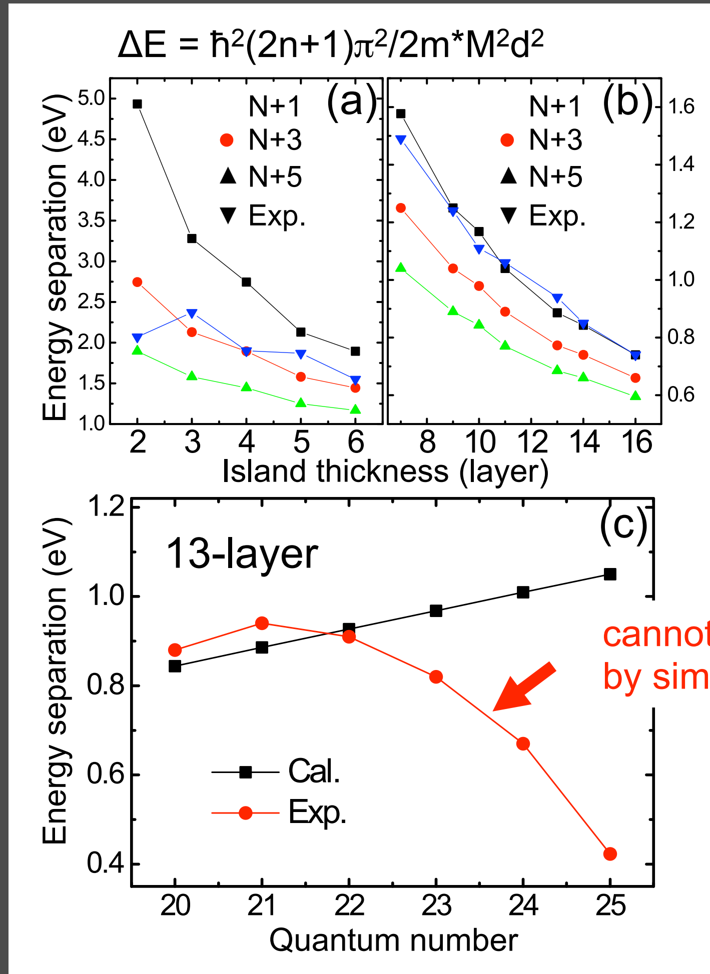
W.B. Jian *et al*., Phys. Rev. Lett. **90**, 196603 (2003)

# Effect of image potential on quantum well states




even

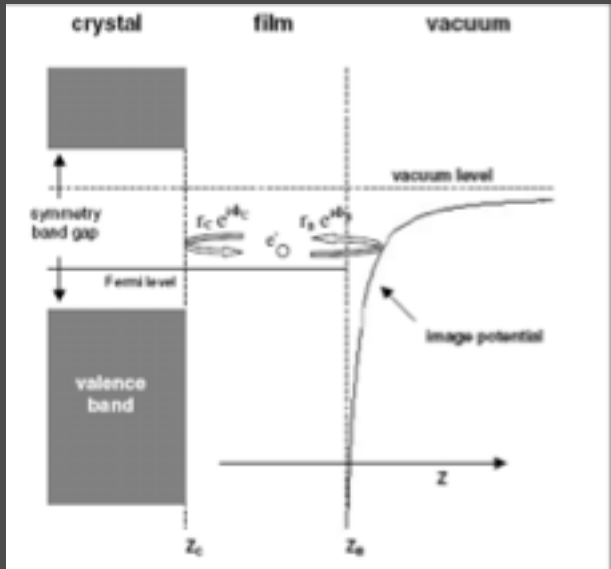
odd

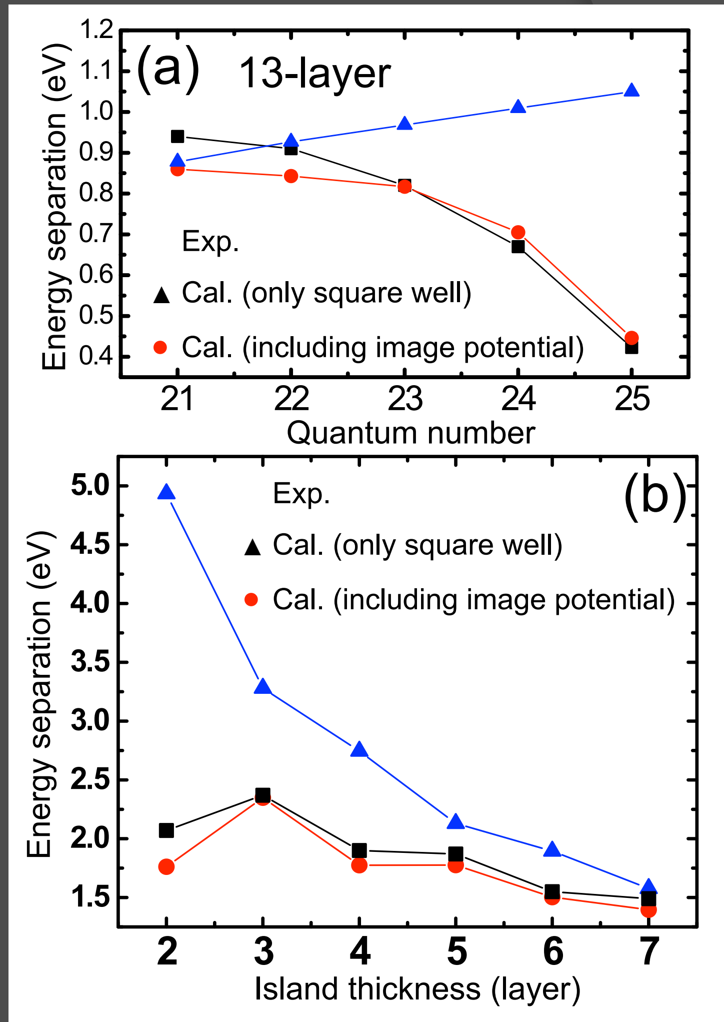



cannot be explained by simple square well

Phys. Rev. Lett. **102**, 196102 (2009)

# Phase contribution of image potential




Phase accumulation (PA) model: total phase=2nπ

For simple square well:

$$2k(N+1)d=2n\pi$$

Including phase $\phi_B$ contributed from image potential

$$2k(N+1)d+\phi_B=2n\pi$$

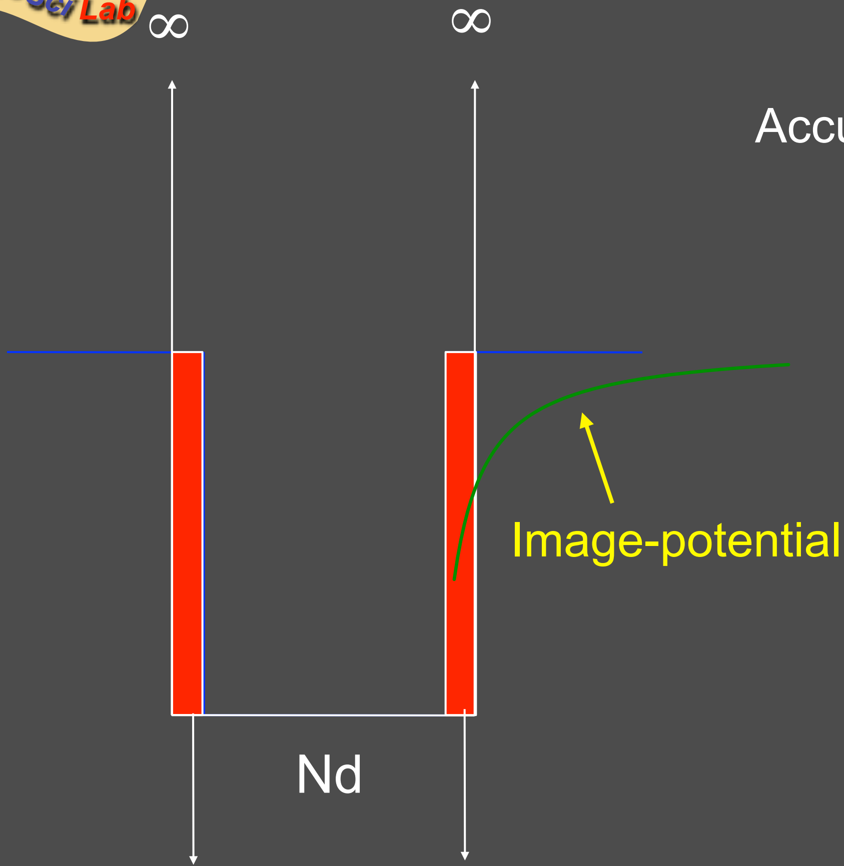
and $\phi_B/\pi=[3.4\ \text{eV}/(E_V-E)]^{1/2}-1$

E: energy of quantum well state

$E_V$: Vacuum level

$E_V$=4.6 eV above $E_F$

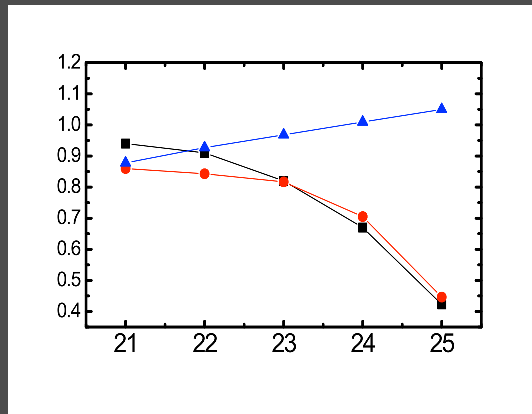
# Accumulative phase model




Penetration depth: d/2

Accumulative phase for quantization:

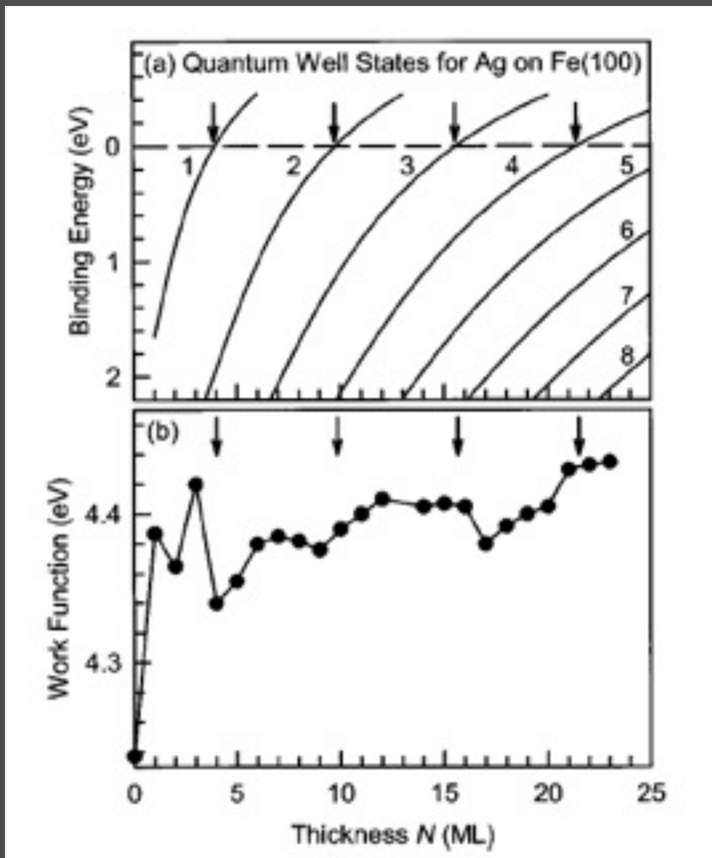
$$2k(N+1)d + \phi_B = 2n\pi$$




Finite square well with width Nd is approximated by infinite square well with width (N+1)d (M=N+1/2+1/2)

# Work function of ultrathin films

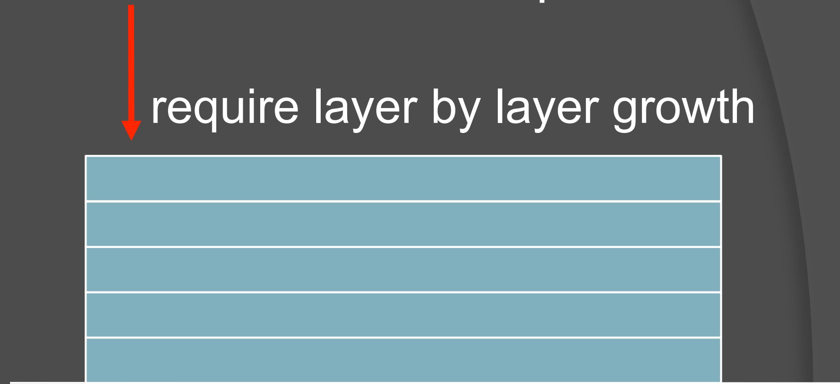
work function measurement for thin film
using photo-emission spectroscopy



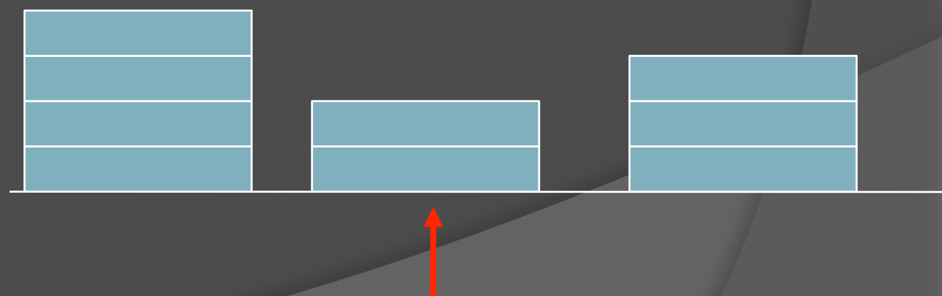

J. J. Paggel et al. 66, Phys. Rev. B (2002) 233403.

Broad beam technique

require layer by layer growth

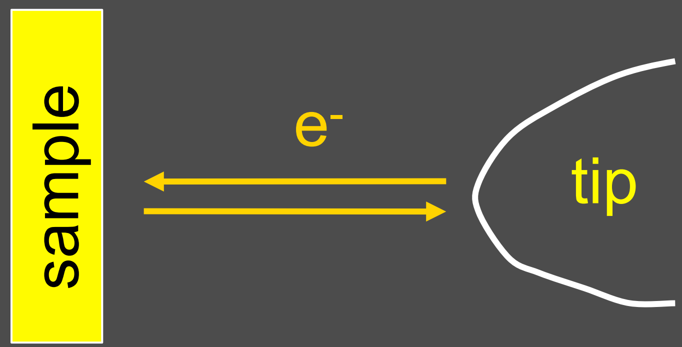


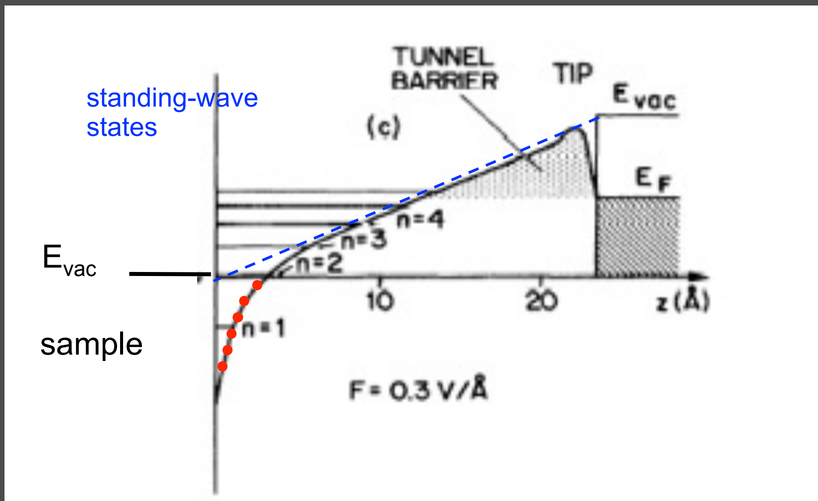
Average work function of various thickness



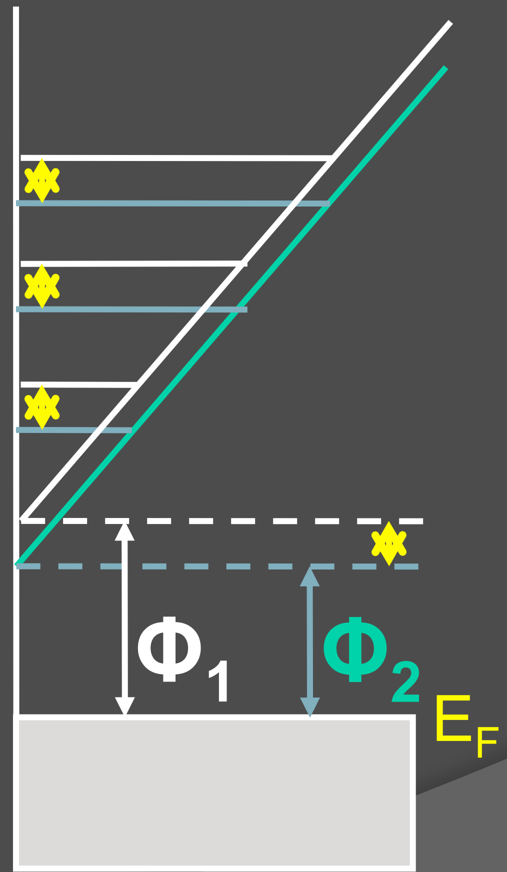
Local probe technique, e.g. STM

# Gundlach oscillation



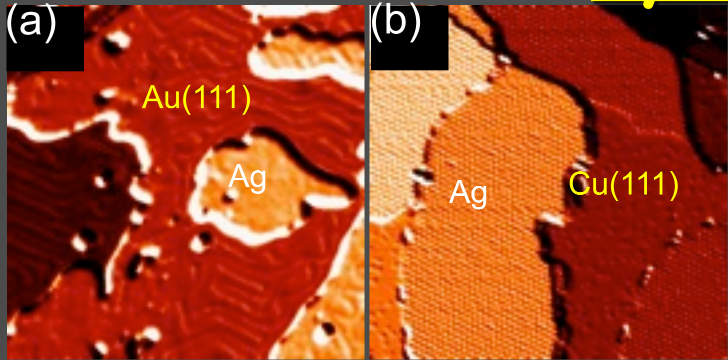



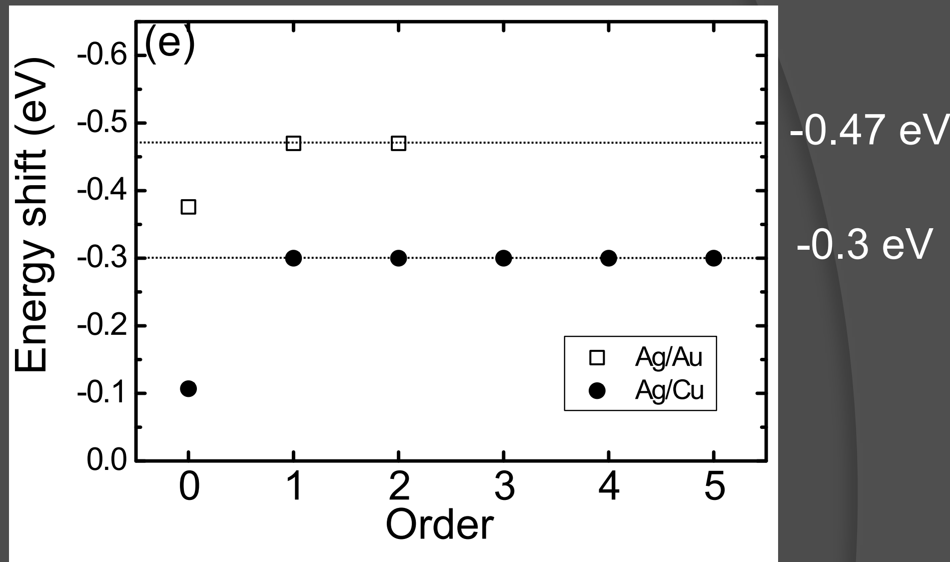

Superposition of image potential and applied potential

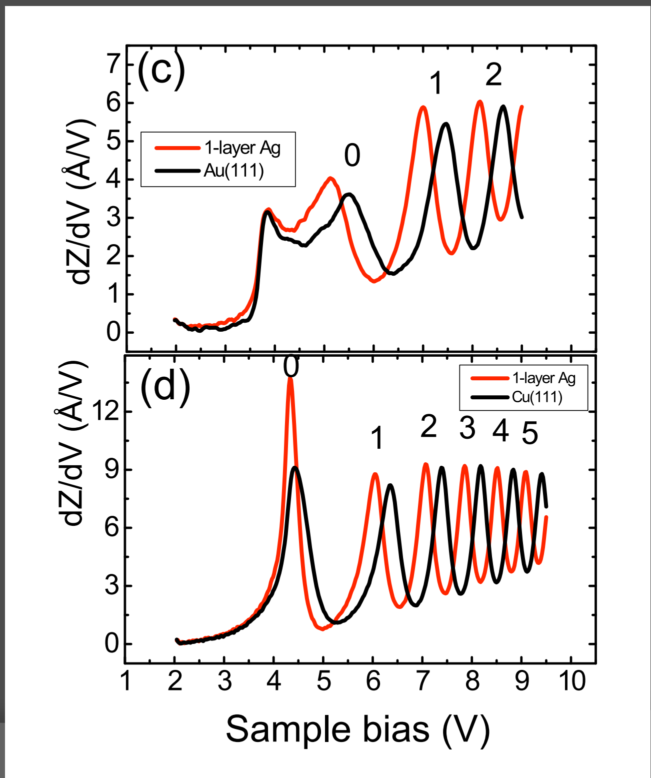



**Constant energy separation = Work function difference**

# Work function measurements by Gundlach oscillation



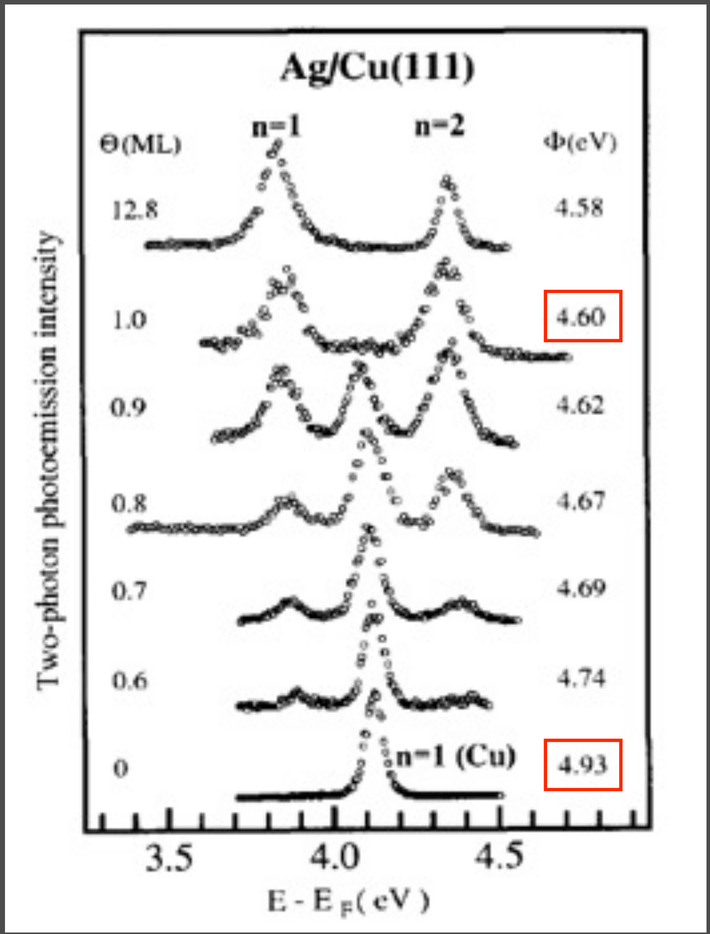




| Bulk Materials | Φ(eV) |
| --- | --- |
| Au(111) | 5.31 |
| Ag(111) | 4.74 |
| Cu(111) | 4.98 |

Lin et al., Phys. Rev. Lett. 99, 216103 (2007)

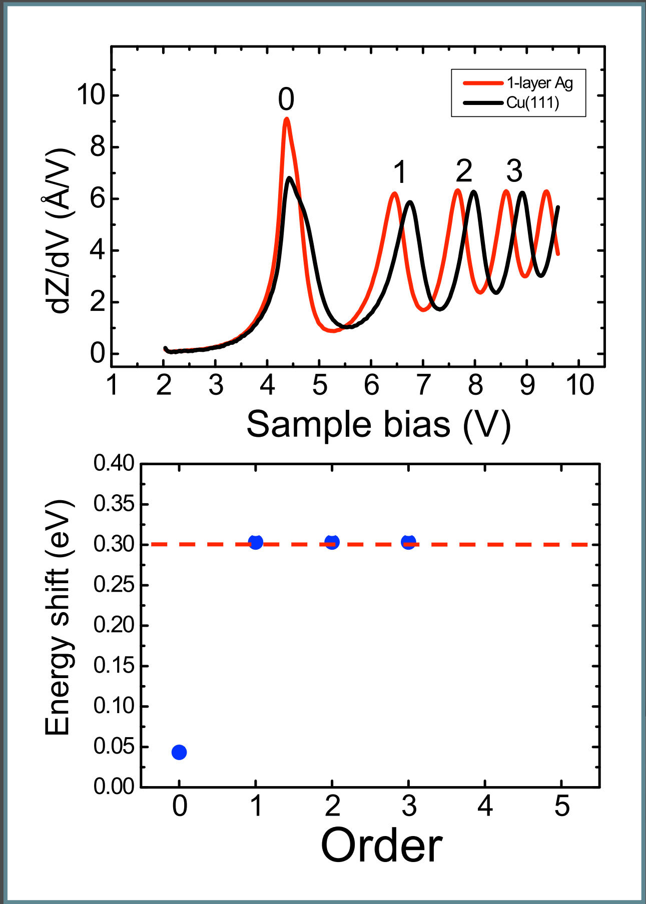
# Comparison with PES measurement

Photoemission (-0.33 eV)

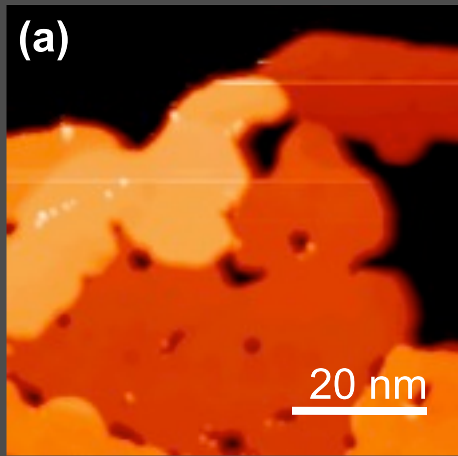


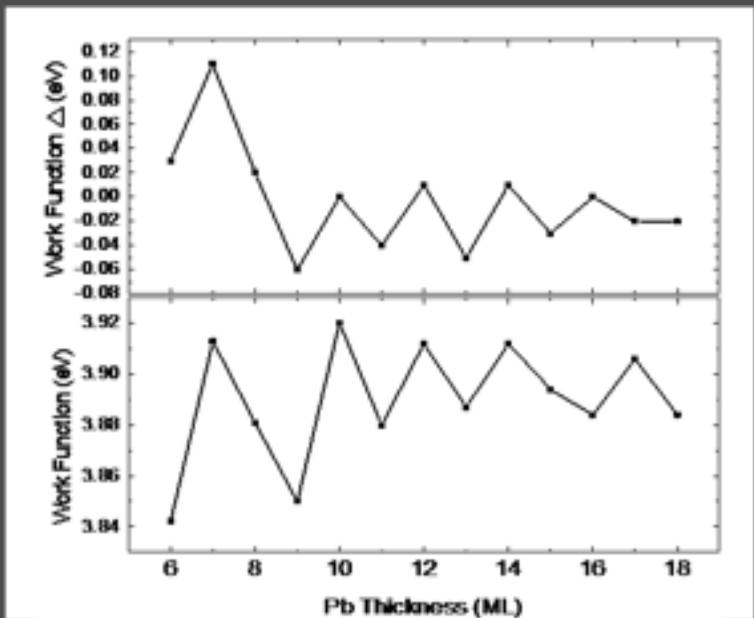

Wallauer et al., Surf. Sci 331, 731 (1995)

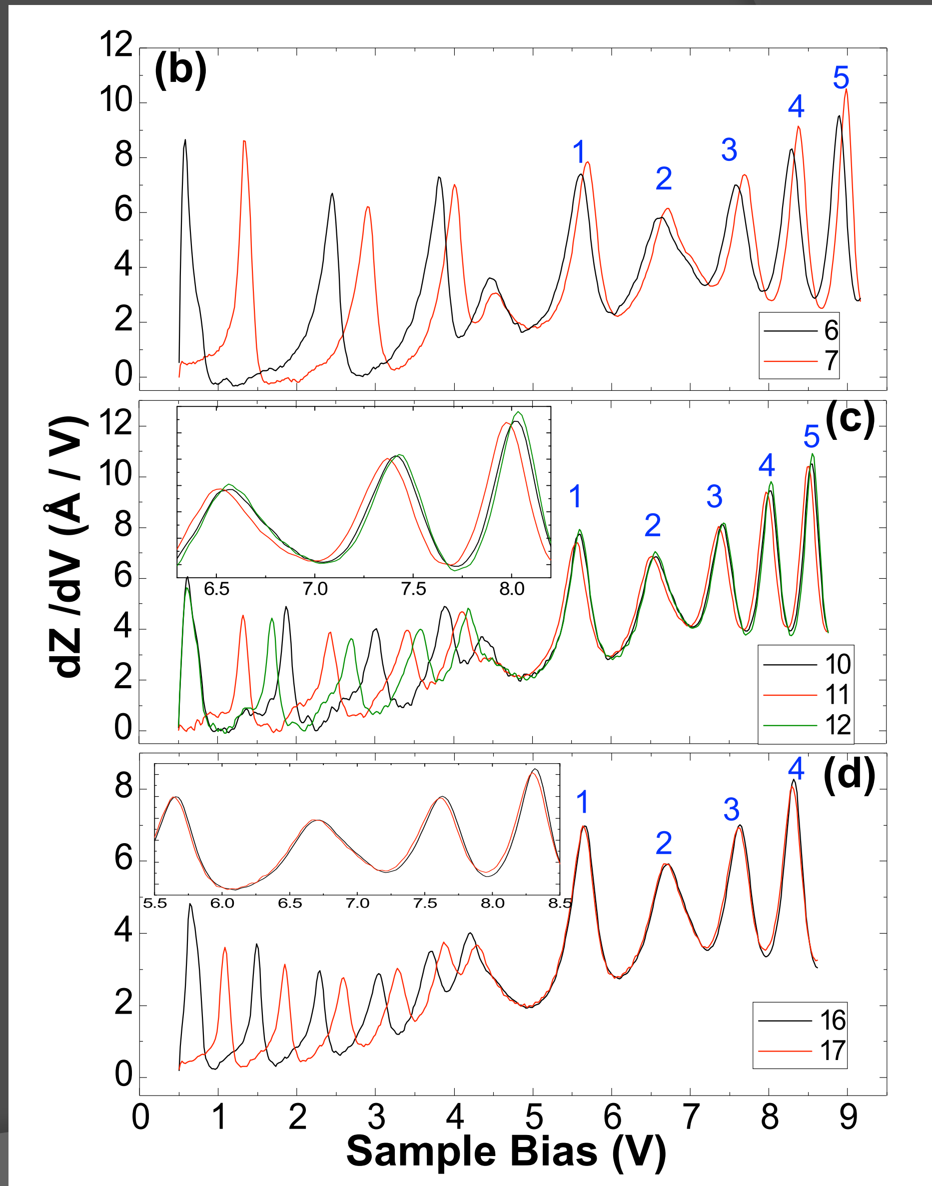
Gundlach oscillation (-0.3 eV)



# Work function differences on Pb films



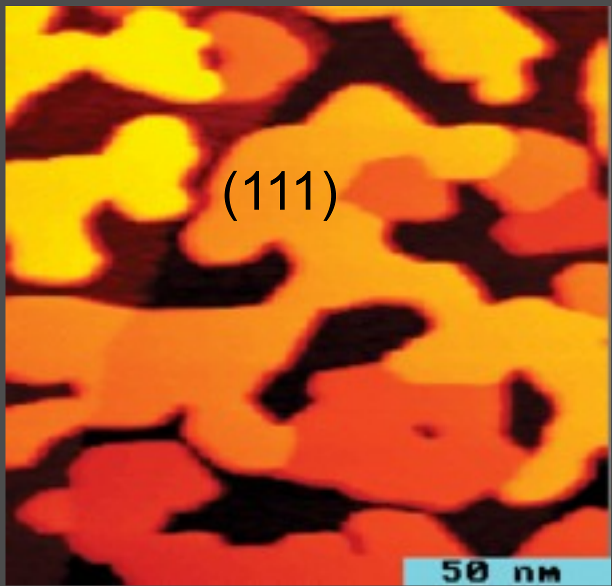



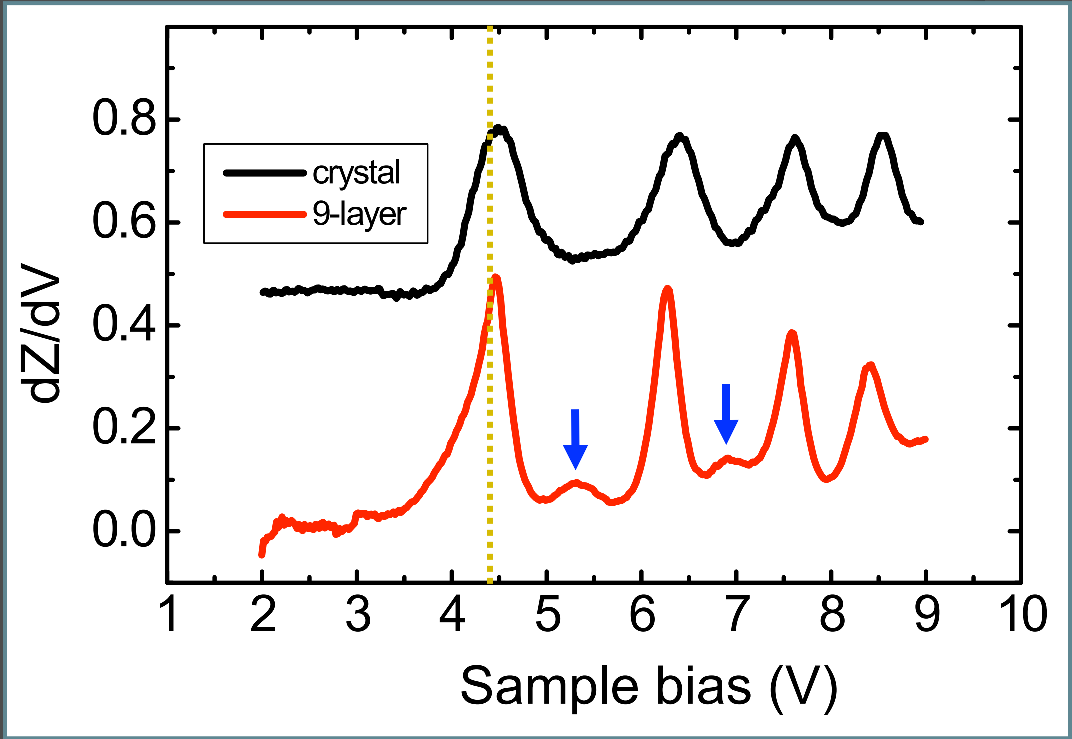




Yu Jia *et al*., Phys. Rev. B 74, 035433 (2006)

# Transmission Resonance in Ag Films on Si(111)

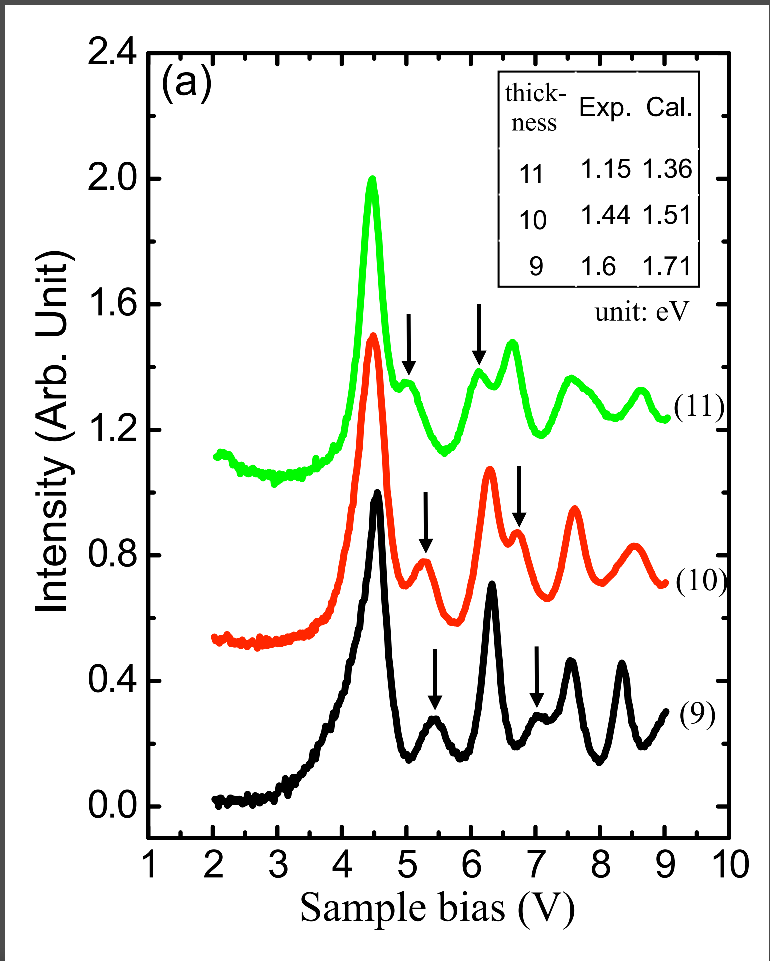
Ag film on Si(111) at RT

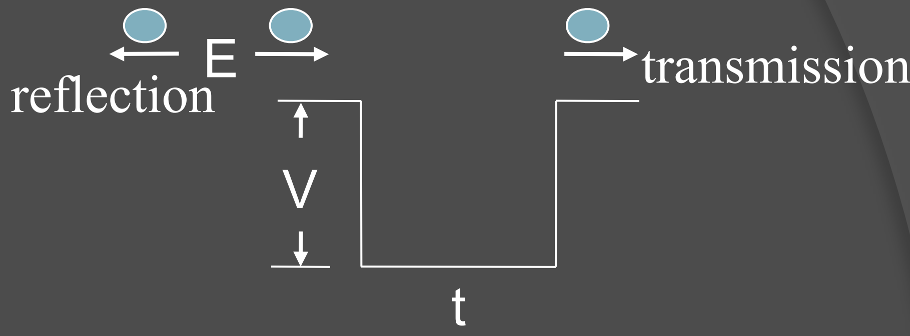



Work function of Ag/Si(111) = 4.41 eV

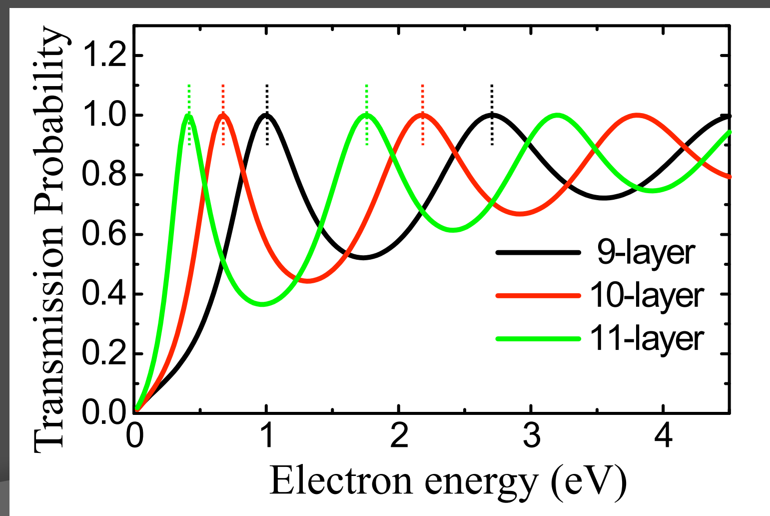
# Quantum Size Effect above Vacuum Level



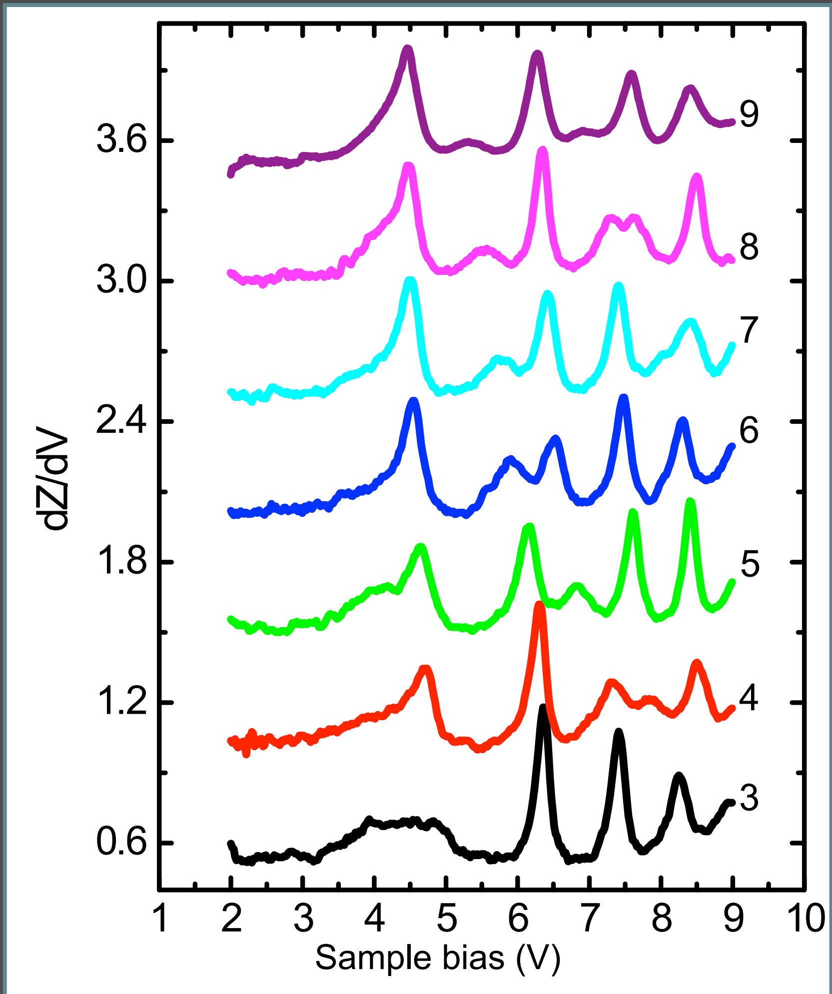




$$\frac{1}{T} = 1+\frac{1}{4}\frac{V^2}{E(E+V)}\sin^2(kt);\ R=1-T;\ \frac{\hbar^2k^2}{2m} = E+V$$

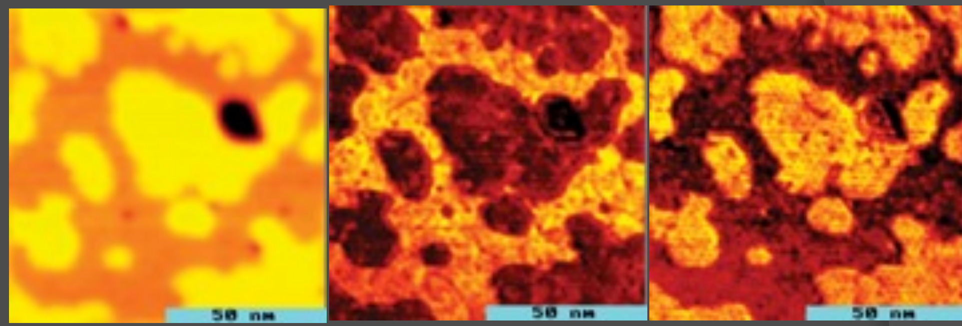
$kt=n\pi \longrightarrow T=1$ transmission resonance

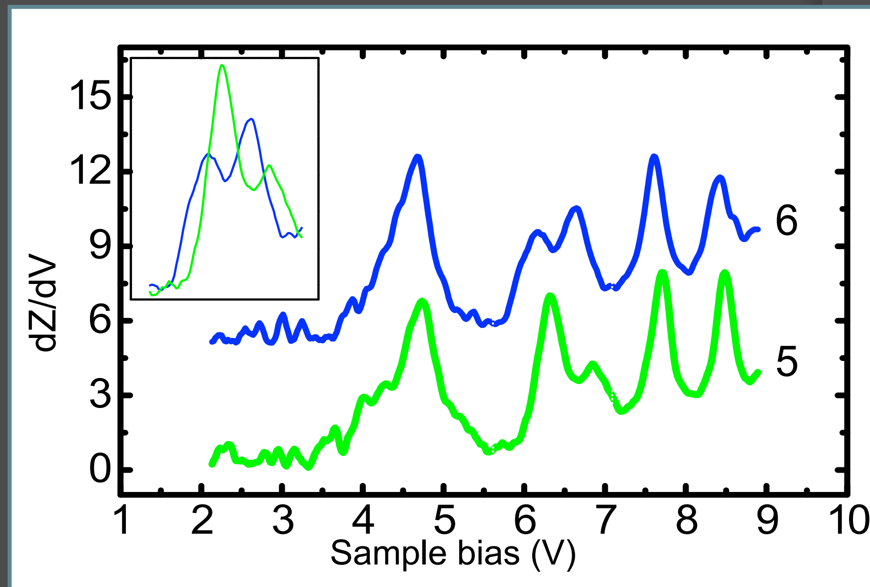


# "Finger print" of film thickness




Low temperature deposition followed annealing to room temperature



## Summary

- Quantum well states are measured with STS in the Pb films of varied thickness on the Si(111) surface.
- The lattice mismatch at the interface produces a periodic potential variation, which manifests in a vertical charge oscillation at the surface, and the subtle phenomena of the complementary and alternating contrast reversals through two types of islands with different stacking are observed.
- The QW states in the energy range of 2 - 5 eV above the Fermi level are affected by the image potential, which causes the shrinking in energy separations with the quantum number.

## Summary

- *A general phenomenon of the constant energy shift is observed in high order Gundlach oscillation.*

  *The work function of a thin metal film can be measured with the constant energy shift better than 0.02 eV, comparable to the photoemission results.*

- *Quantum transmission resonance can be observed with STS in Ag films on the Si(111) surface.*

  *Positions of the transmission resonance measured with STS can serve as finger prints for the Ag films of varied thickness.*

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C. L. Lin, S. M. Lu, M.C. Yang, H.Y. Chou,
W.B. Jian, H.Y. Lin, Y.P. Chiu, and C.M. Wei

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