Surface and Nano Sciences Lab
(www.phys.sinica.edu.tw/~nano/)

Nanoscience

FIM, SPM, TEM

Calculations and simulations
Theoretic work

LT STM + magnet
Single spin detection, quantum phenomena in nanostructures

Nanotechnology

New tools, new instruments, new methods

Surface dynamics, epitaxial growth, atom manipulation, bio-imaging

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

UHV TEM + STM

Surface and Nano Sciences Lab

Tien T. Tsong (1990)
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I. S. Hwang (1994)
W. B. Su (2001)
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2010年12月16日星期四
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.
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

Visibility

\[ V = \frac{(I_{\text{max}} - I_{\text{min}})}{(I_{\text{max}} + I_{\text{min}})} \]

\[ V = \frac{69405 - 8484}{69405 + 8484} = 0.78 \]

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.

Nanotechnology 20, 115401 (2009)
Scanning Tunneling Microscopy

References:


Pt(001) reconstructed Surface

Surface Science 306, 10 (1994)
Surface and interface properties of ultrathin metal films on Si and Cu substrates

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Outline

- Quantum well states in ultrathin Pb films
  - Manifestation of interfacial potential
  - Effect of image potential

- Gundlach oscillations in STM configuration
  - Work function measurements

- Transmission resonance through thin films
  - Determination of film thickness
Scanning Tunneling Microscopy

References:
Various quantum phenomena

- Energy
- Si(111) Cu(111)
- Vacuum level
- Transmission resonance
- Gundlach oscillation
- Quantum well states
- Ag or Pb

NanoSciLab
Scanning Tunneling Spectroscopy

\[ I \propto \int_{0}^{eV} \rho_s(E_F-eV+\varepsilon) \rho_T(E_F+E\varepsilon)d\varepsilon \]

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

Sample

Tip

(Feedback off)

I-V spectrum

(Feedback on)

Z-V spectrum

\( \frac{dI}{dV} \) scanning sample
Pb islands on the IC Pb/Si(111)
Quantum size effect

$\lambda = \text{de Broglie wavelength of electron}$

$a = \text{thickness of metal film}$
Spectra for Pb Films

\[ d_0 = 2.85 \text{ Å} \quad \lambda_F = 3.94 \text{ Å} \]

\[ 2d_0 \approx 3(\lambda_F/2) \]

C.M. Wei and M.Y. Chou
Apparent island heights

![Image of apparent island heights]

- Layer (N) vs. Relative height (Å) graph showing layer thickness variations.
- Chart indicating apparent island heights with specific values in Å.
Difference in layer stacking
Characteristics of Pb islands---
Bias-dependent imaging contrast

Const. current  dl/dV mapping

Type I
filled-state
type I empty-state

Type II
filled-state
type II empty-state
Characteristics of Pb island: oscillatory and complementary contrast

Effect of image potential on quantum well states

![Pb island/Cu(111)](image)

Even

Odd

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 = 2nπ

Including phase $\phi_B$ contributed from image potential

2k(N+1)d + $\phi_B$ = 2nπ

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

E: energy of quantum well state
E_V: Vacuum level

$E_V = 4.6 \text{ eV above } E_F$
Finite square well with width $Nd$ is approximated by infinite square well with width $(N+1)d$ ($M=N+1/2+1/2$)

Accumulative phase model

Accumulative phase for quantization:

$$2k(N+1)d + \phi_B = 2n\pi$$
Work function of ultrathin films

work function measurement for thin film using photo-emission spectroscopy


Broad beam technique
require layer by layer growth

Average work function of various thickness

Local probe technique, e.g. STM
**Gundlach Oscillation**

Sample $\leftrightarrow$ Tip

Superposition of image potential and applied potential

Constant energy separation = Work function difference
Work function measurements by Gundlach oscillation

(a) Au(111) Ag (b) Ag Cu(111)

(c) and (d) dZ/dV (Å/V) vs. Sample bias (V)

(e) Energy shift (eV) vs. Order

Bulk Materials \( \Phi (\text{eV}) \)

<table>
<thead>
<tr>
<th>Material</th>
<th>( \Phi ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au(111)</td>
<td>5.31</td>
</tr>
<tr>
<td>Ag(111)</td>
<td>4.74</td>
</tr>
<tr>
<td>Cu(111)</td>
<td>4.98</td>
</tr>
</tbody>
</table>

Comparison with PES measurement

Photoemission (-0.33 eV)

Gundlach oscillation (-0.3 eV)

Work function differences on Pb films

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

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

\[kt = n\pi \quad \rightarrow \quad T = 1 \text{ transmission resonance}\]
"Finger print" of film thickness

Low temperature deposition followed annealing to room temperature
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.
Acknowledgment


Thank you for your attention