Quantum Properties of Atomically Uniform Pb Films on Si

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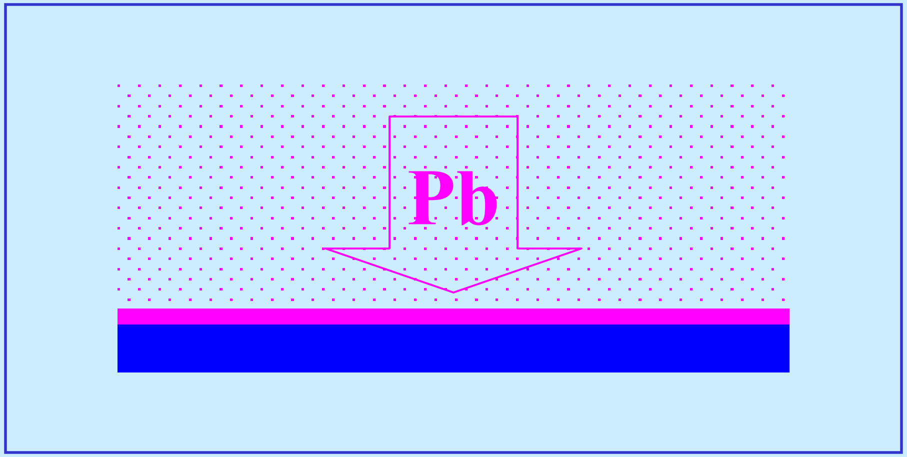
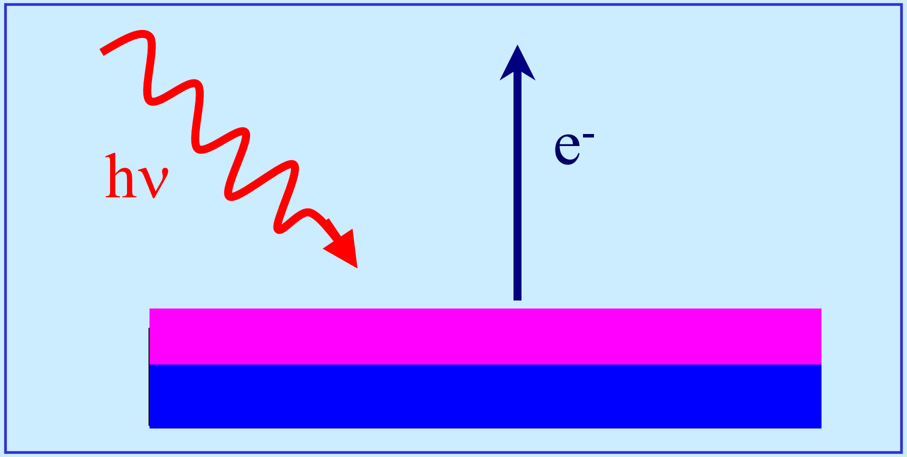
- Introduction
- Growth mode of Pb/Si(111)
- Bilayer Electronic Oscillations
- Dispersion in Pb/Si(111) films
- Thermal Stability of Pb/Si(111) films

Experiment

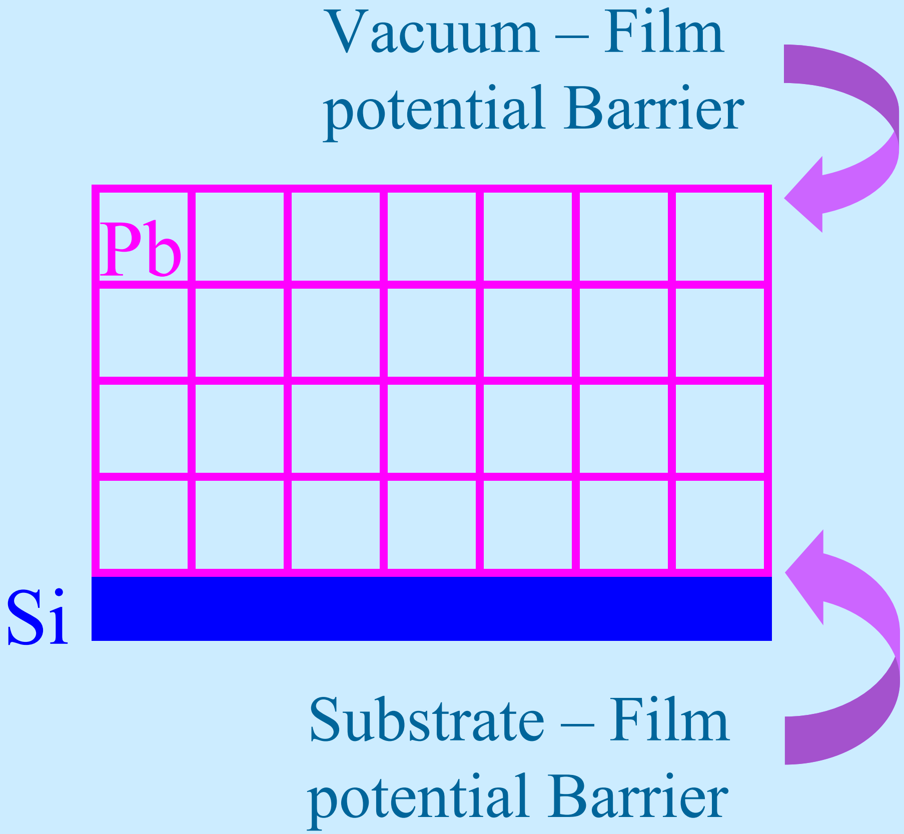
1. Grow Pb on 100 K Si(111)- ($\sqrt{3}$x $\sqrt{3}$) – Pb α (4/3 ML) or β (1/3 ML) reconstruction with Molecular Beam Epitaxy (MBE).
2. Study sample with photoemission (photons in, electrons out)





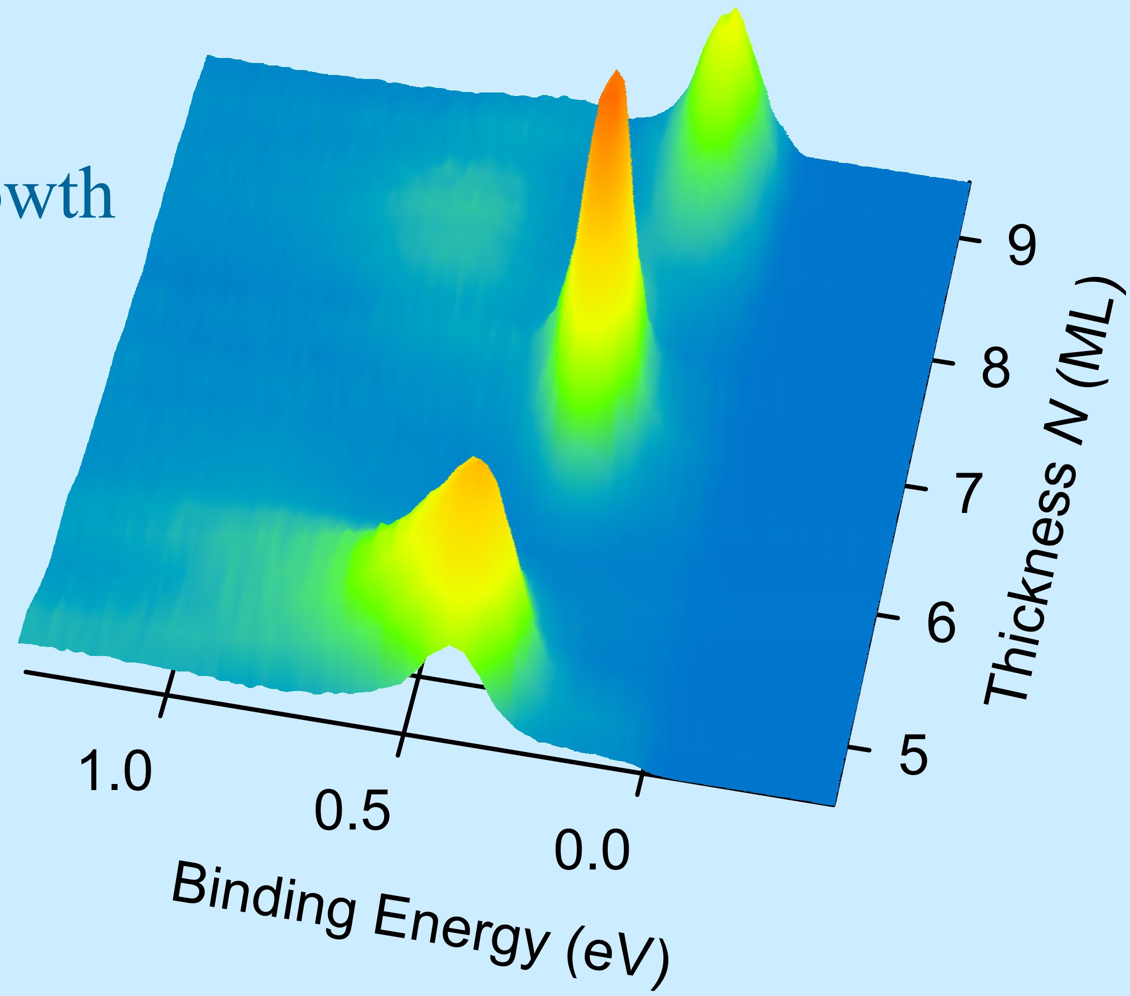
Quantum Well States

- Electron confined in film ⇒ Particle in a box states
- Need close to layer-by-layer growth to see states.



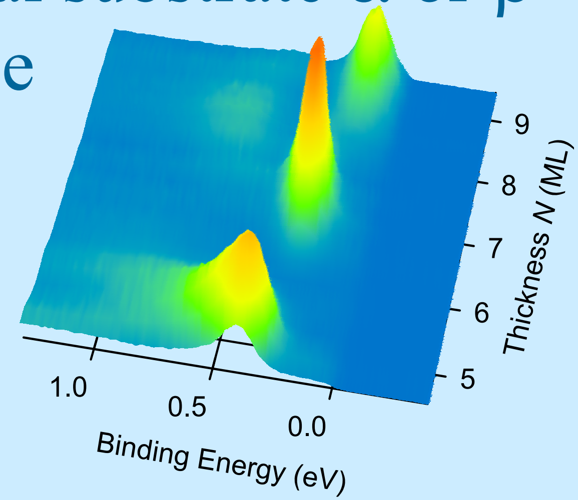
Pb/Si Layer by Layer Growth

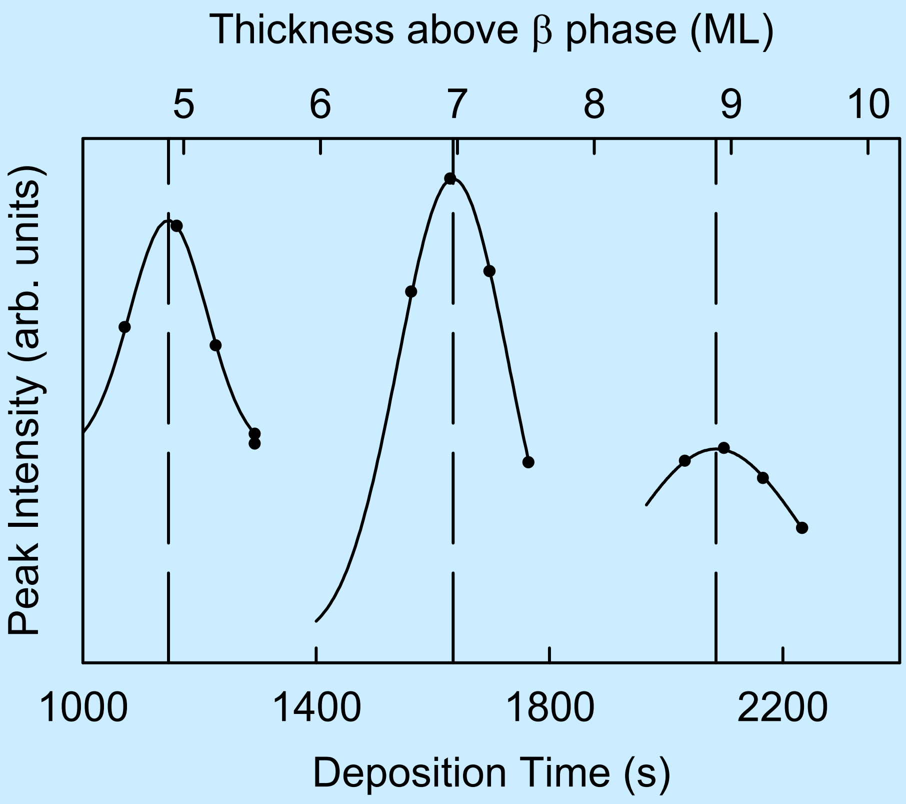
- Layer by layer growth
- Odd ML→sharp, intense peaks
  Even ML→broad shallow peaks



Film Thickness Determination

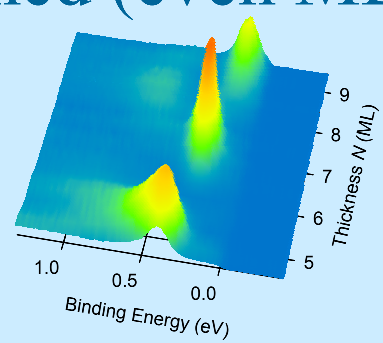
- Deposition time between 1st and 3rd major peak is 4 ML
- Seconds/ML gives total thickness of film
- Initial substrate α or β phase

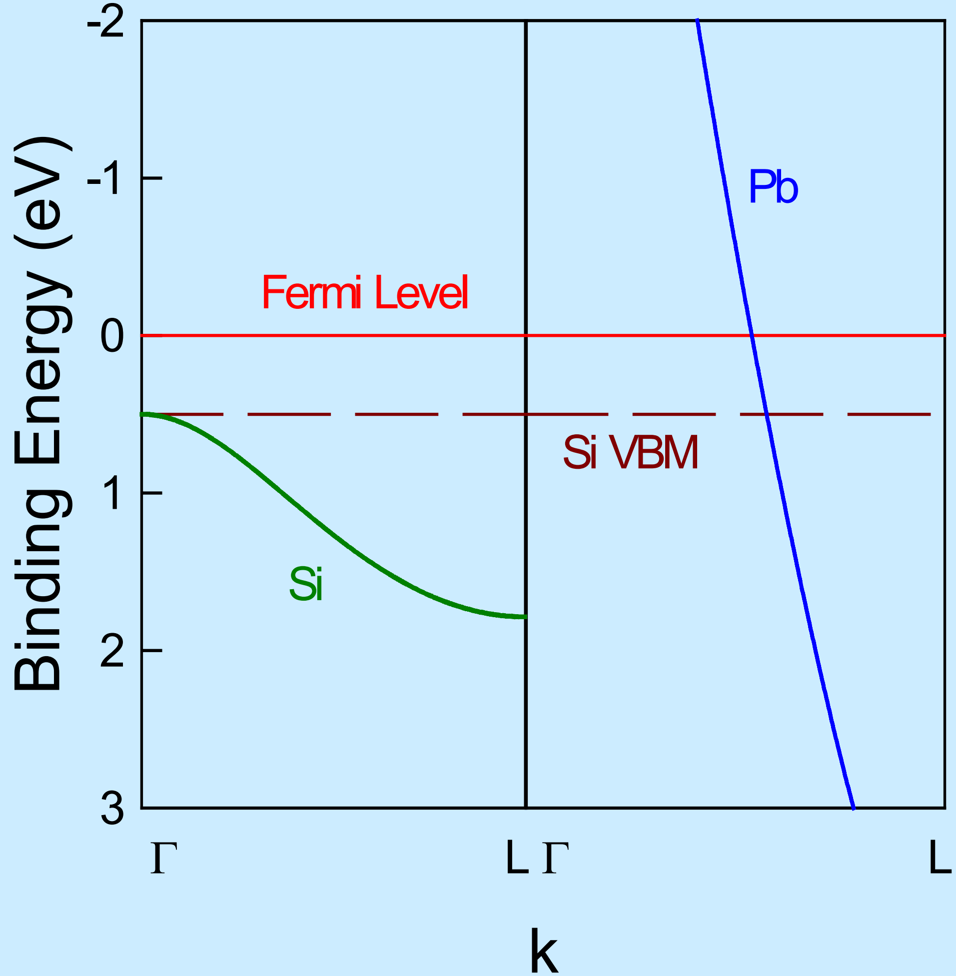




Quantum Wells/ Resonances

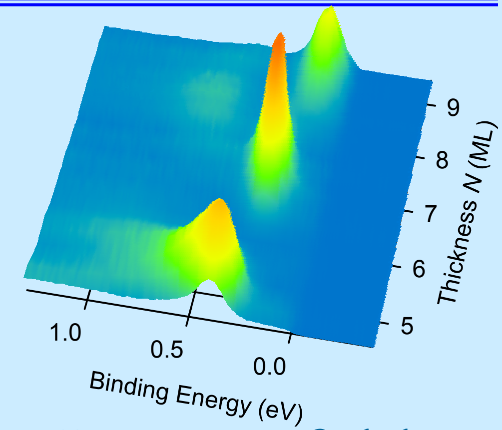
- Good confinement between Si VBM and Fermi Level
- Quantum well states well confined (odd ML)
- Resonances not well confined (even ML)

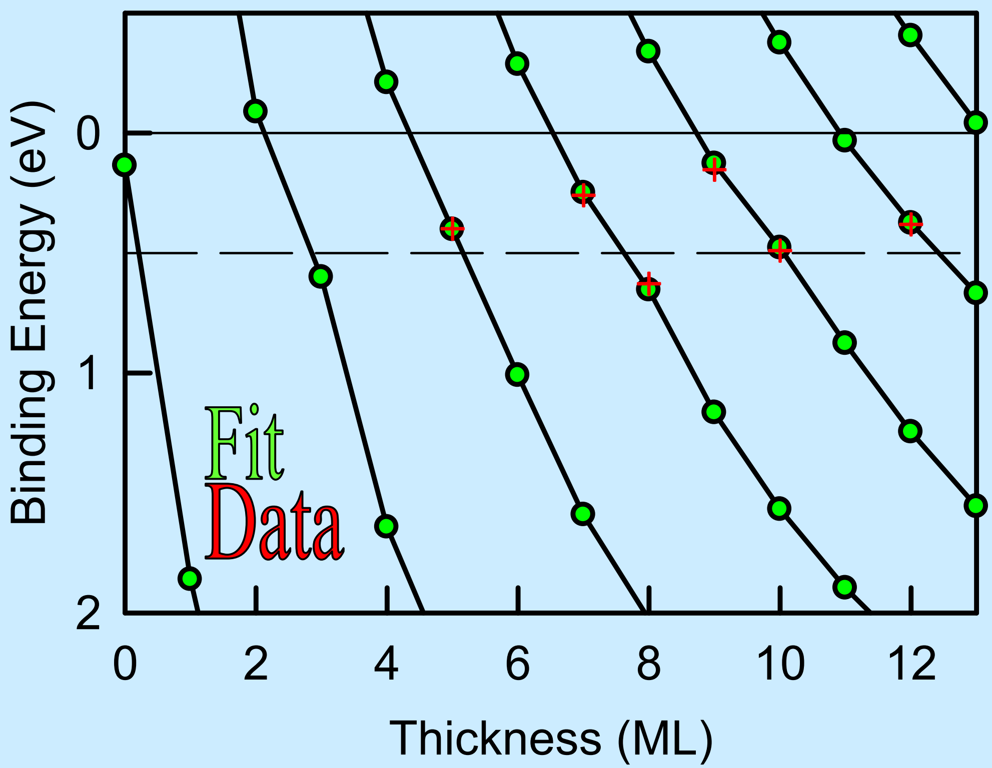




Film Electronic Structure

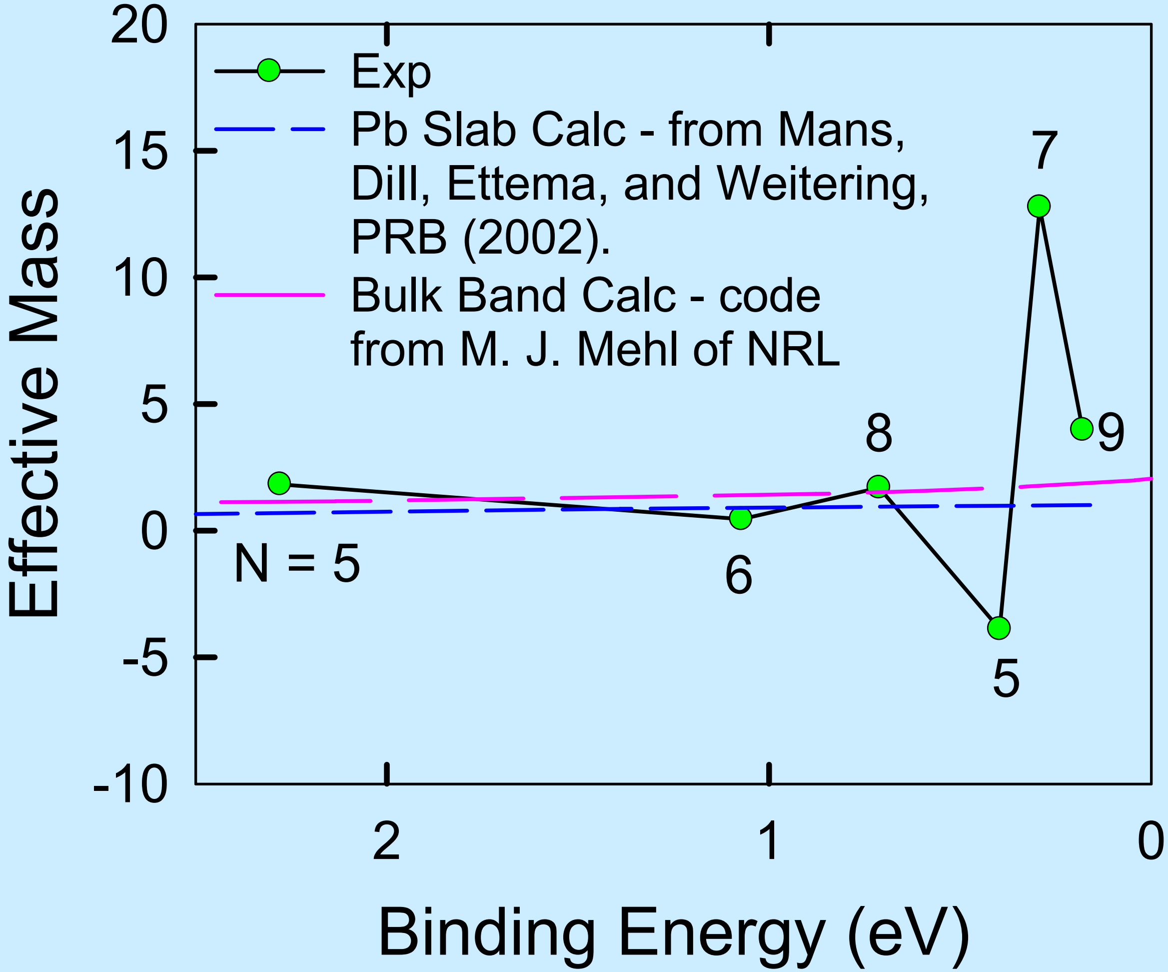
$$\underbrace{2k(E)d}_{\text{phase change in film}} + \underbrace{\phi_V(E)}_{\text{at vacuum}} + \underbrace{\phi_I(E)}_{\text{at interface}} = 2\pi n$$



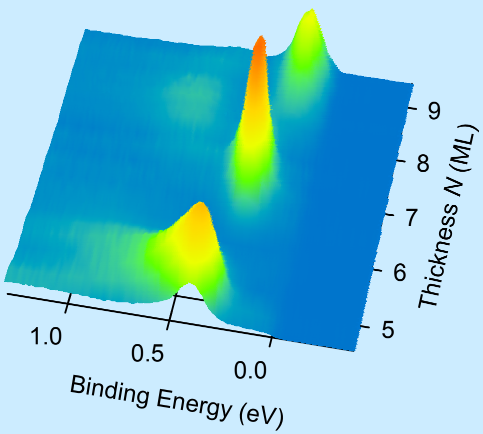


- Bohr-Sommerfeld model
- Theoretical form for boundary phase shifts
- One parameter fit

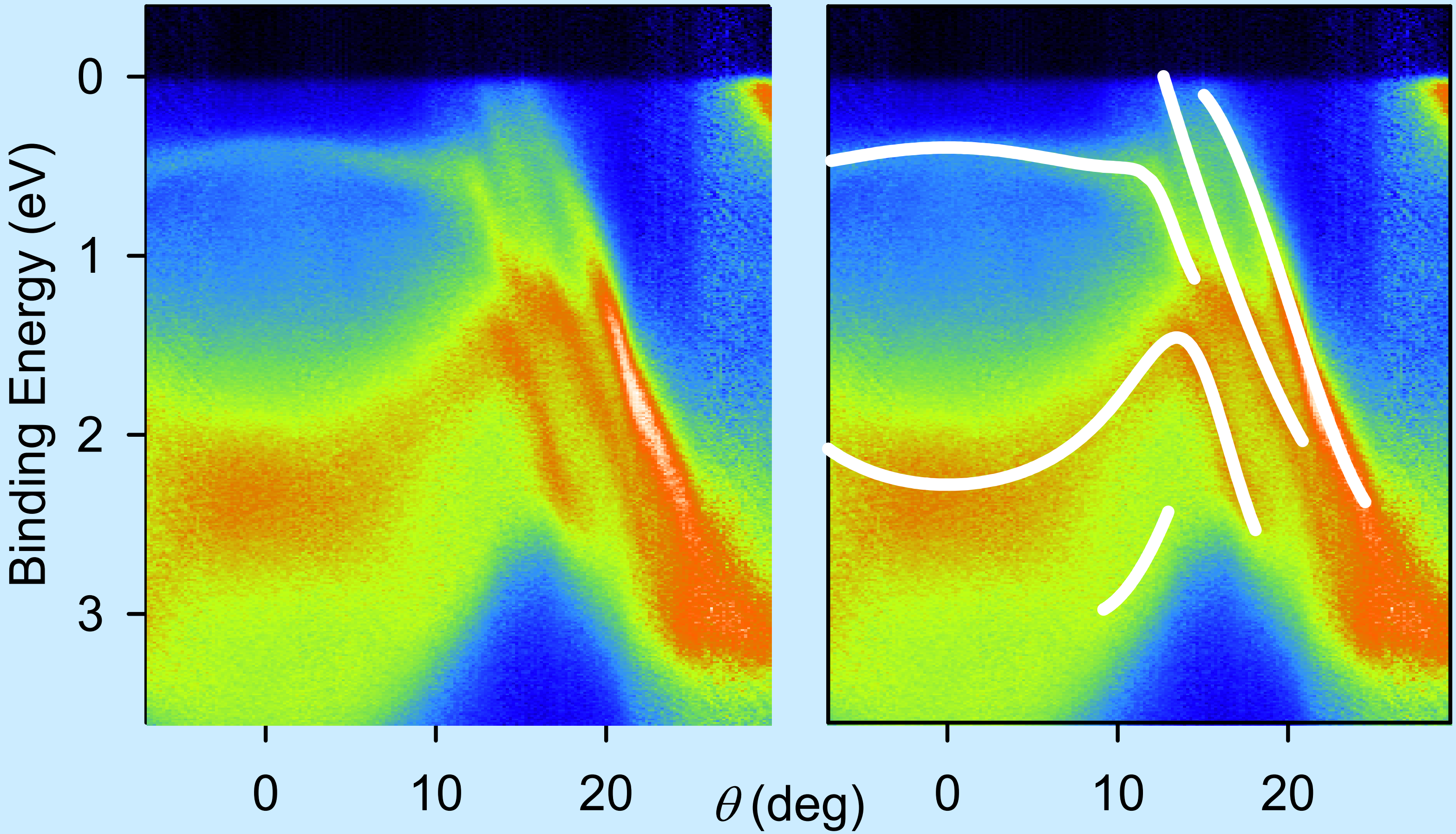
Effective Mass



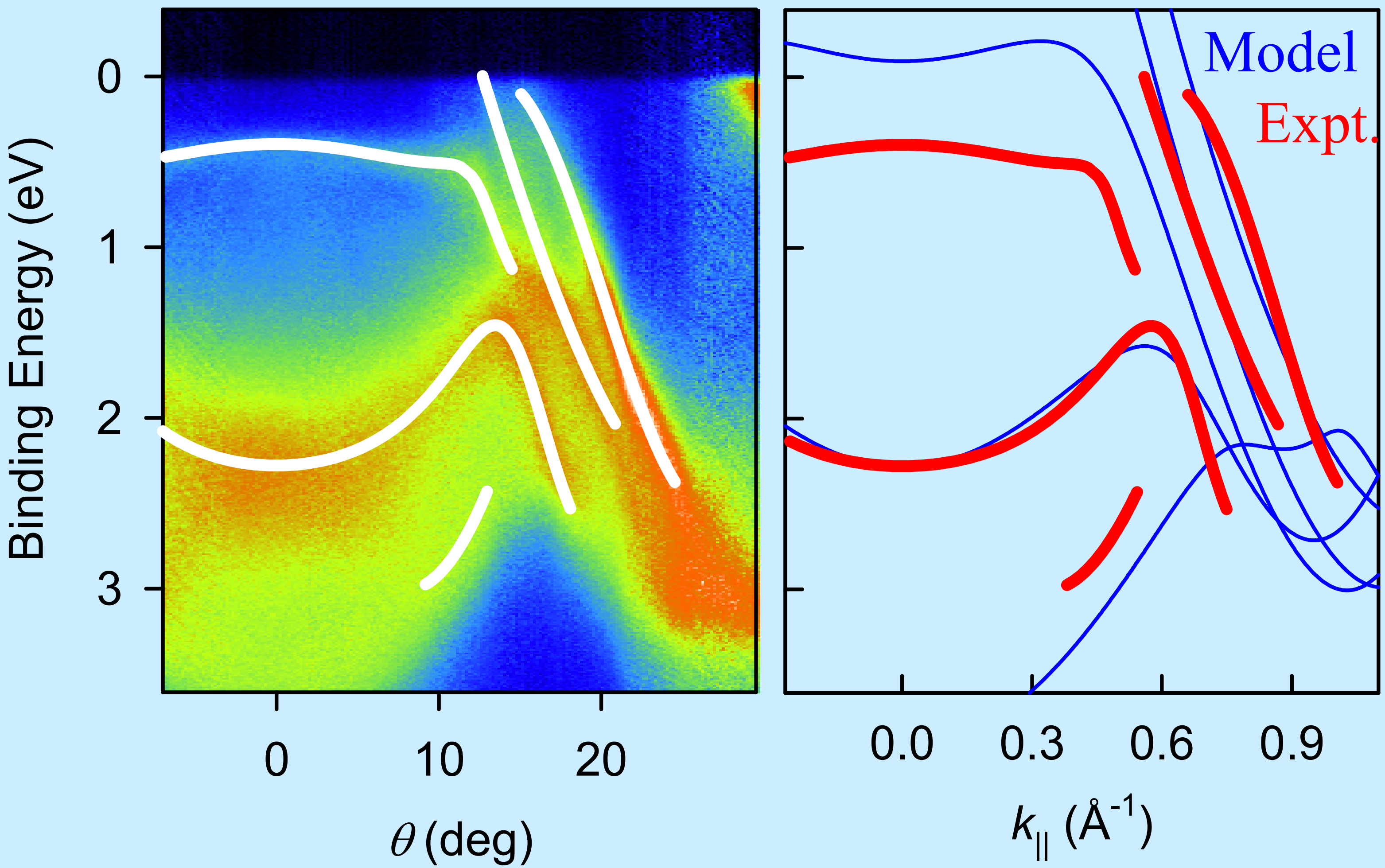
- Theory good at high BE
- Aberrant effective mass near Si VBM



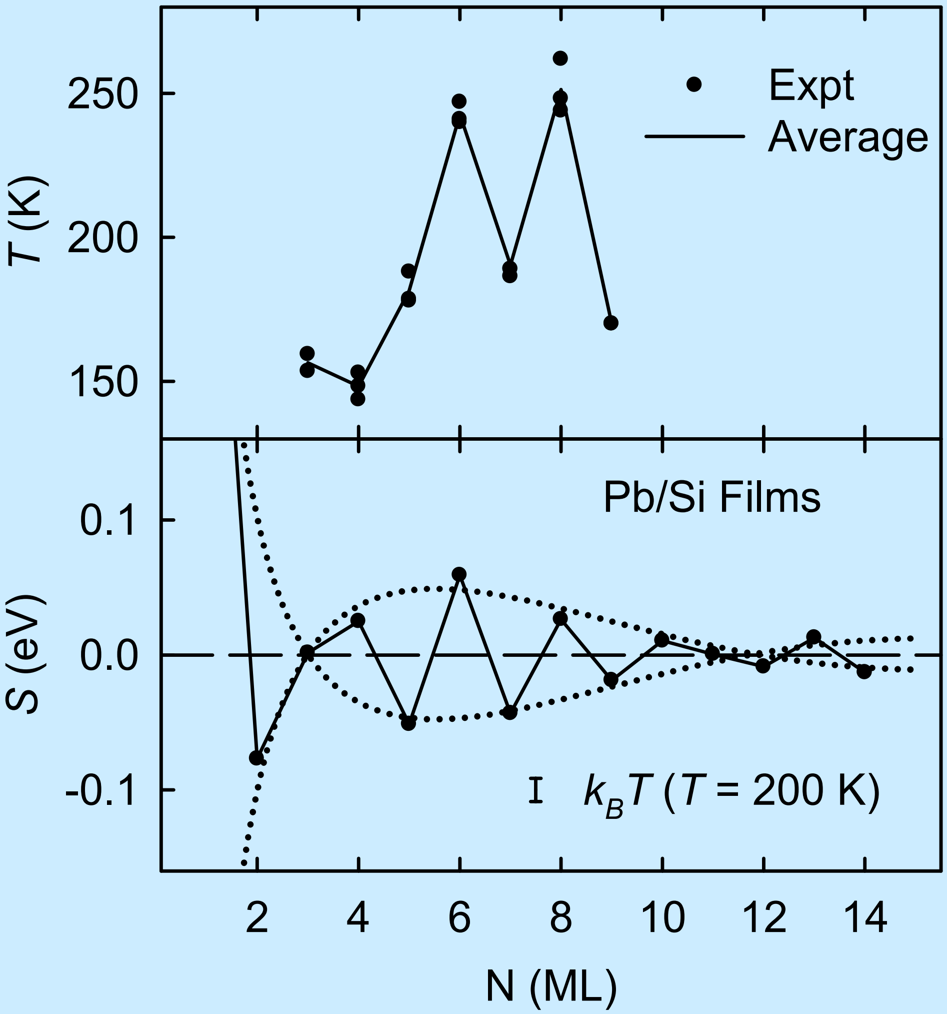
Dispersion Measurement – 5ML



Dispersion Measurement – 5ML



Thermal Stability



- 5-9 ML has bilayer oscillation as predicted
- Low ML unusually unstable

Calculation

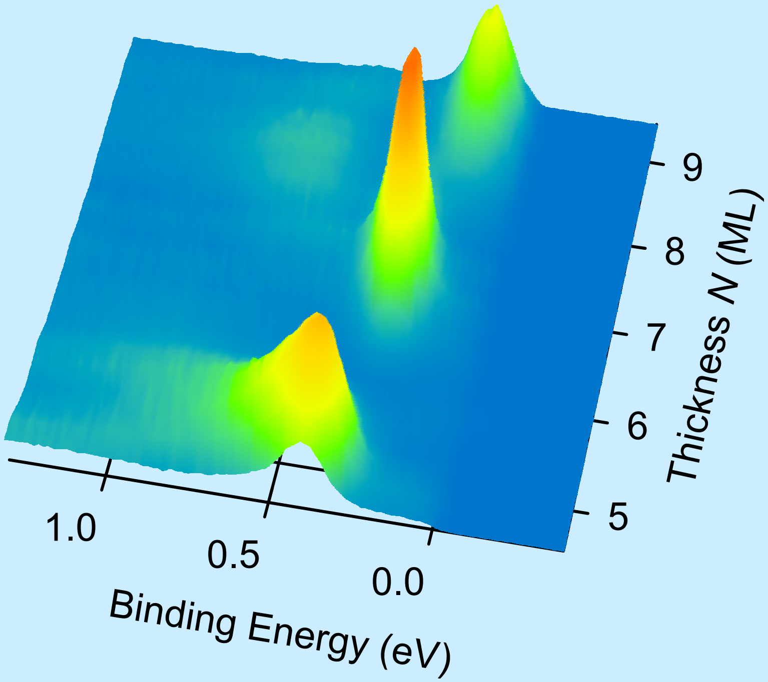
- S = 2nd derivative of Surface Energy

$$S = \frac{E(N+1) + E(N-1)}{2} - E(N)$$

- Si lattice is compressed to match Pb lattice

Summary

- Atomically uniform films
- Bilayer electronic oscillations
- Quantum well sub-band dispersion
- Thermal stability of films shows even-odd oscillations



•M. H. Upton, C. M. Wei, M. Y. Chou, T. Miller, and T.-C. Chiang, “Thermal Stability and Electronic Structure of Pb films on Si(111)”, PRL, accepted.

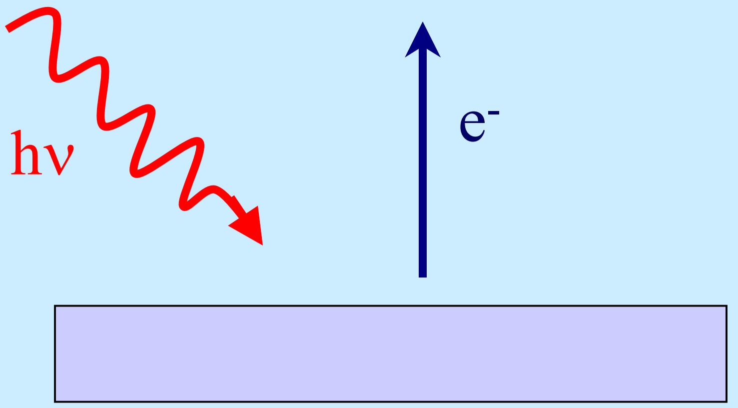
•M. H. Upton, T. Miller, and T.-C. Chiang, “Absolute Determiniation of Film Thickness from Photoemission: Application to Atomically Uniform Films of Pb on Si”, APL, accepted.

•M. H. Upton, T. Miller, and T.-C. Chiang, “Anomalous Parallel Dispersion in Atomically Uniform Films”, PRL, submitted.

Backups follow

Photoemission

- Photons in, electrons out
- Electronic structure of sample from momentum of escaping electrons



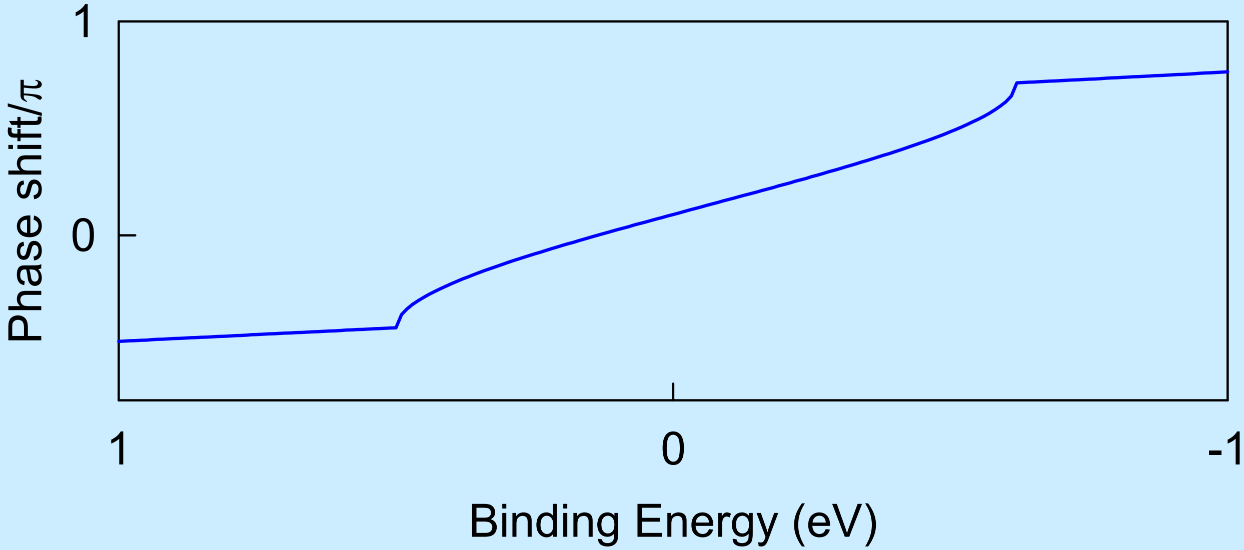
Phase Shift

$$\phi_{\text{Pb/Si}} = \text{Re}\left[-\cos^{-1}\left(2\frac{E-E_L}{E_U-E_L}-1\right)\right]+\phi_0$$

from N. V. Smith, Phys. Rev. B **32**, 3549 (1985).

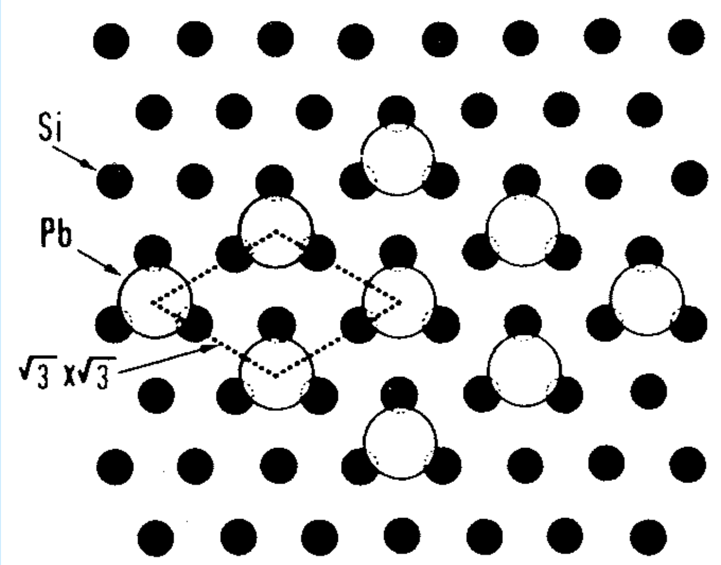
$$\phi_{\text{Pb/Vacuum}} = A\left[\text{Re}\left[-\cos^{-1}\left(2\frac{E-L}{U-L}-1\right)\right]+B\right]$$

A, B, U, L fit to phase shift in C. M. Wei, M. Y. Chou, PRB **66**, 233408 (2002).

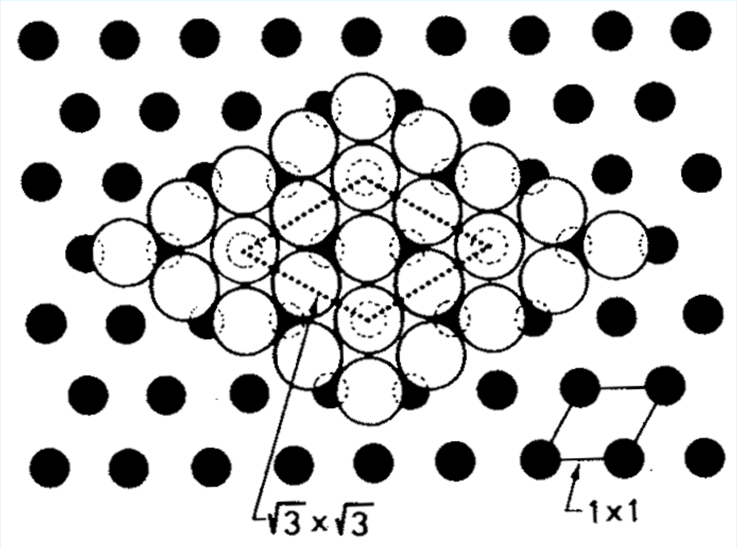


√3x √3 Pb/Si(111) Surface

- β: 1/3 ML Pb/Si

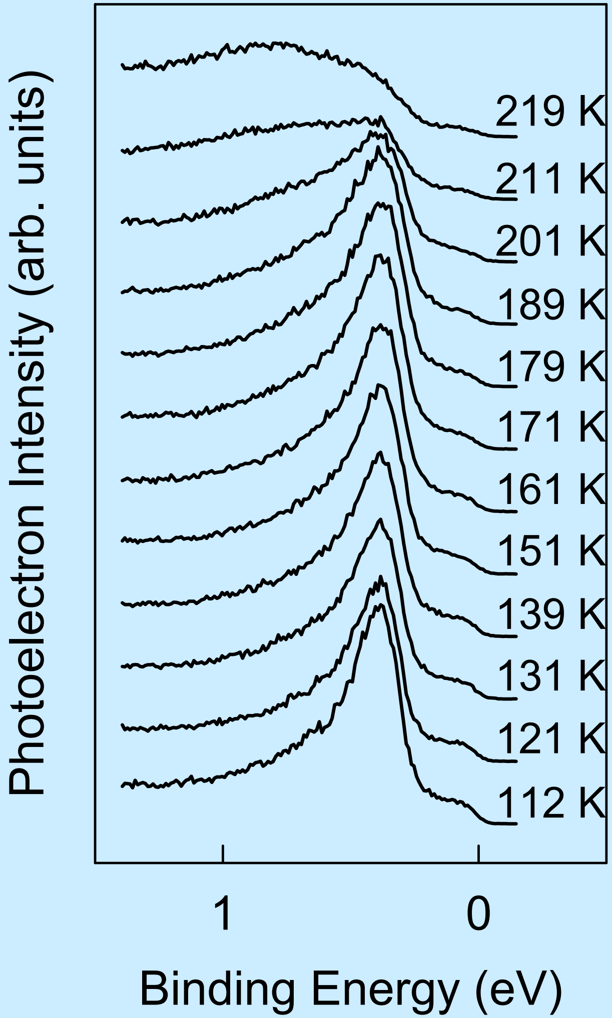


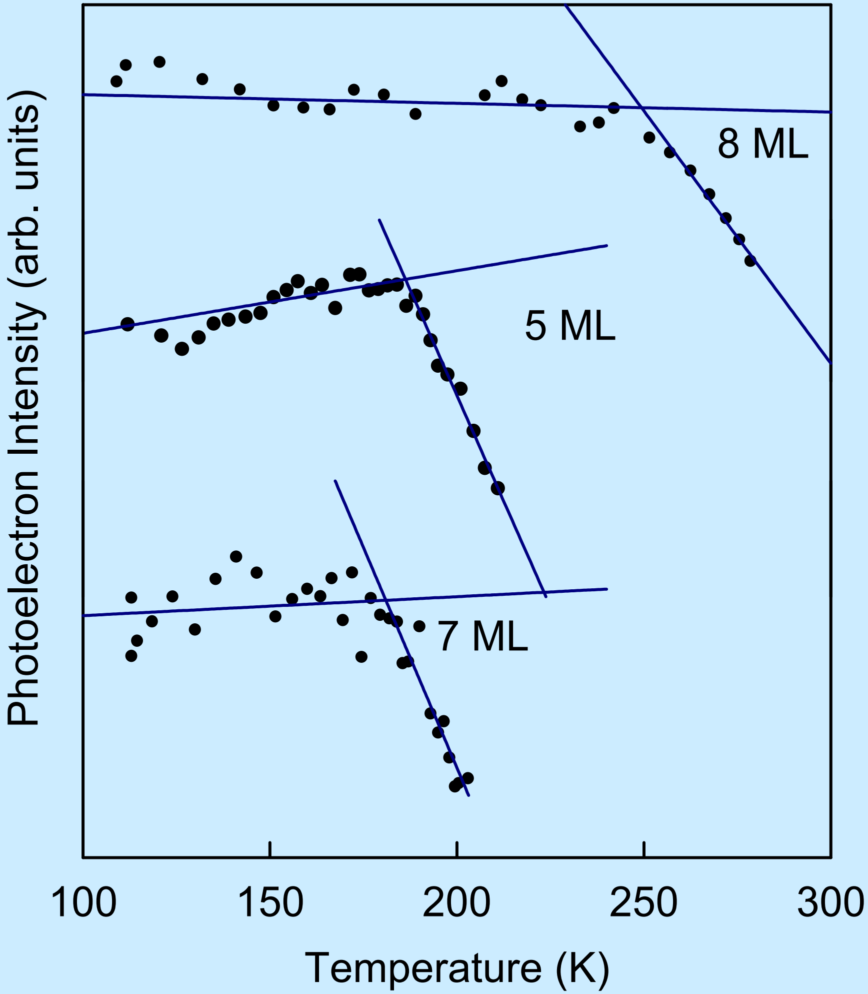
- α: 4/3 ML Pb/Si



Illustrations from Saitoh et al. Surface Science **154**,394 (1985).

Measuring Thermal Stability

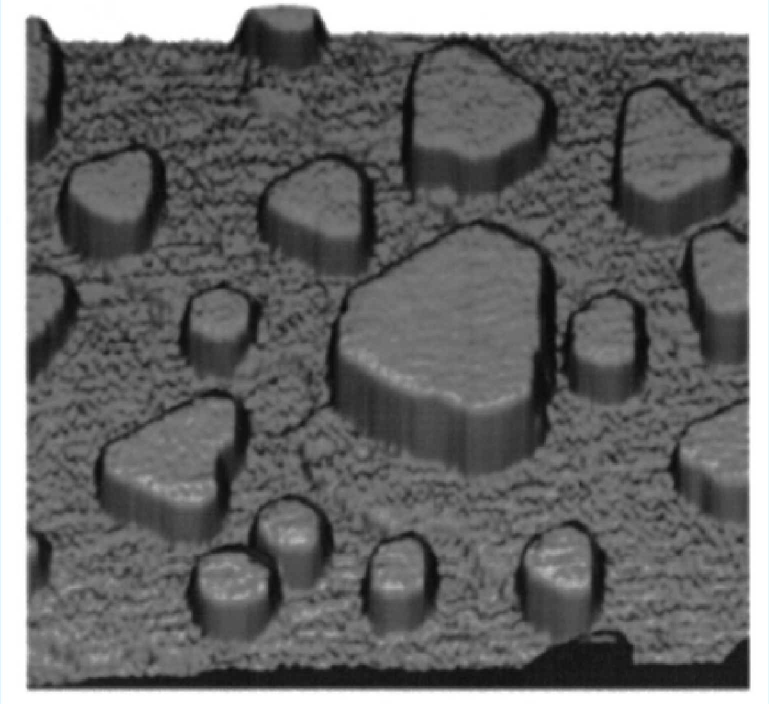




STM Results

•200 K growth, 5-7-9 … ML grow sequentially on β phase *Hupalo, Yeh, Berbil-Bautista, Kremmer, Abram, and Tringides PRB 2001.*

•77 K growth, flat topped islands observed at coverages 5-35 ML on annealed interface *Altfeder, Narayanamurti, and Chen PRL 2002.*



3 ML at 200 K on β phase *Hupalo et al.*