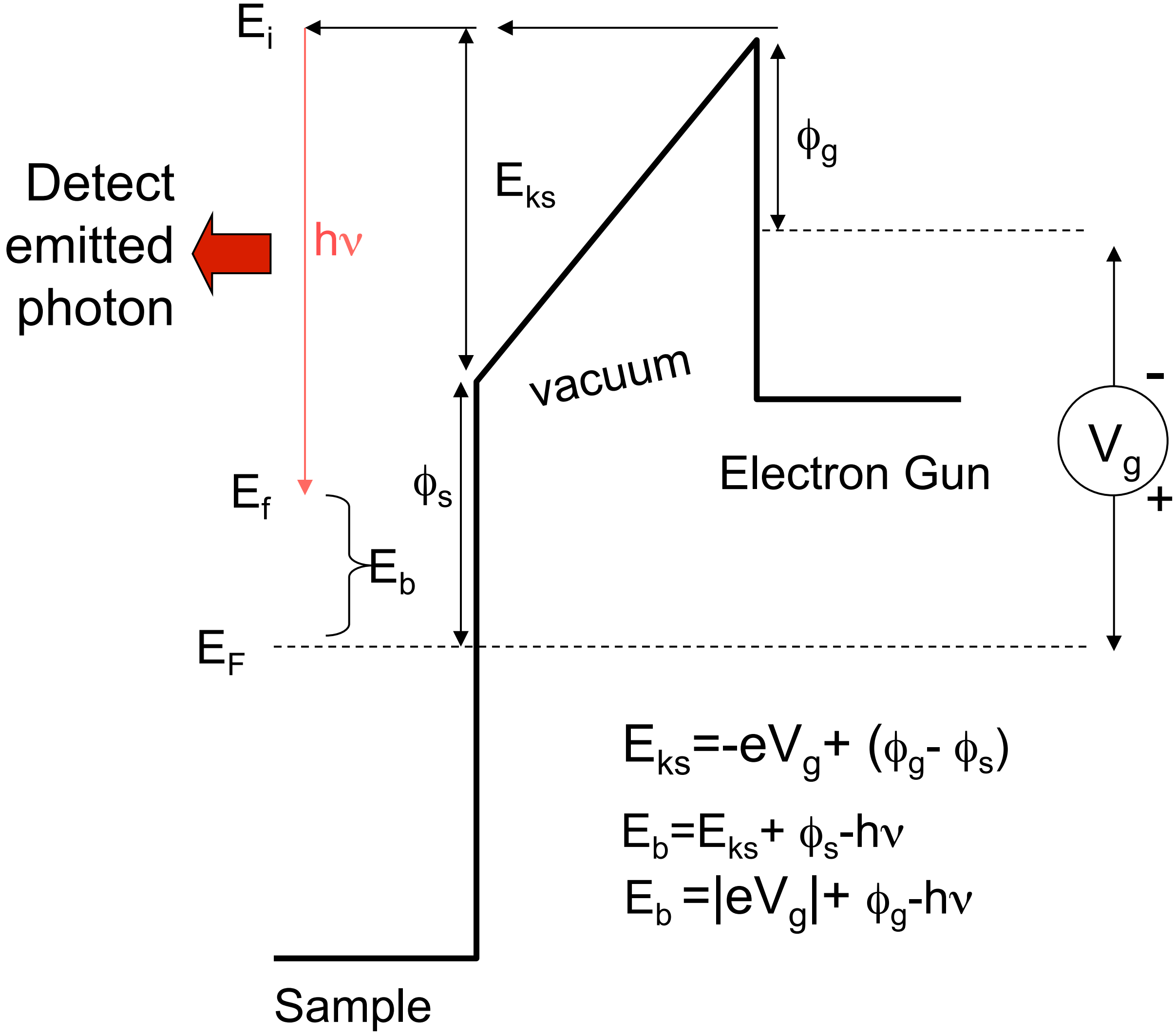
# Inverse Photoelectron Spectroscopy
# IPES

- Sometimes called Bremsstrahlung Isochromat Spectroscopy (BIS)
- Complement to UPS
  - UPS: Photon in, electron out
  - IPES: Electron in, photon out
- IPES probes the unoccupied density of states (ie states above the Fermi level)
- Can be Angle-Resolved (k-Resolved)
  - Known as ARIPES or KRIPES
  - Surface scientists love acronyms

# Description of IPES




$$E_{ks} = -eV_g + (\phi_g - \phi_s)$$

$$E_b = E_{ks} + \phi_s - h\nu$$

$$E_b = |eV_g| + \phi_g - h\nu$$

Binding energy of $E_i$ with respect to the Fermi Energy is given by: $E_b = |eV_g| + \phi_g - h\nu$

# Electron Gun

- Energy range 5-15 eV
  - Difficult to design. Low energy electrons susceptible to space charge effects (energy/spatial spread due to e-e interactions)
- Thermionic emission of electrons from a heated cathode
- Energy spectral width is determined by the temperature of the cathode.
  - Maxwell-Boltzmann-like distribution
  - Want high resolution
  - Low work function cathode results in lower emission temperature
  - BaO typical. Can achieve $\Delta E(FWHM)\sim 0.22$ eV

# Typical Electron Energy Spectrum

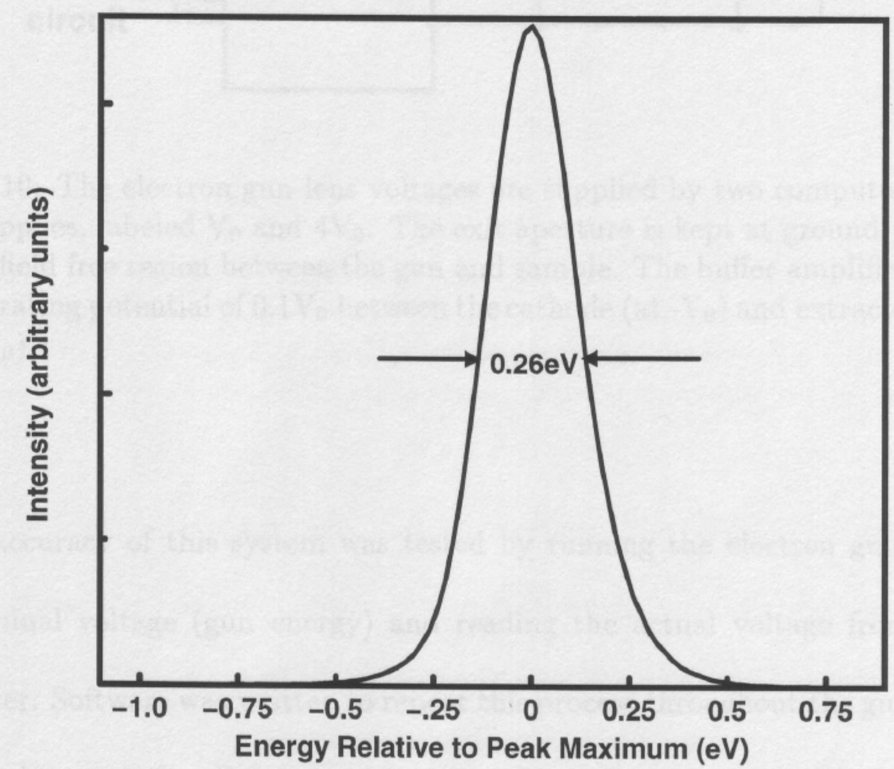
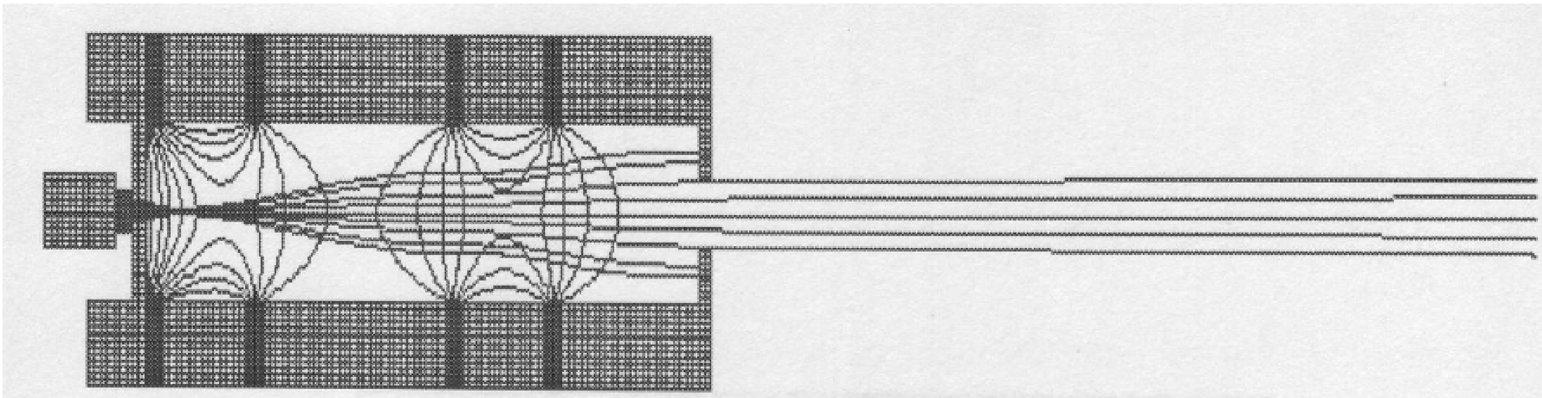
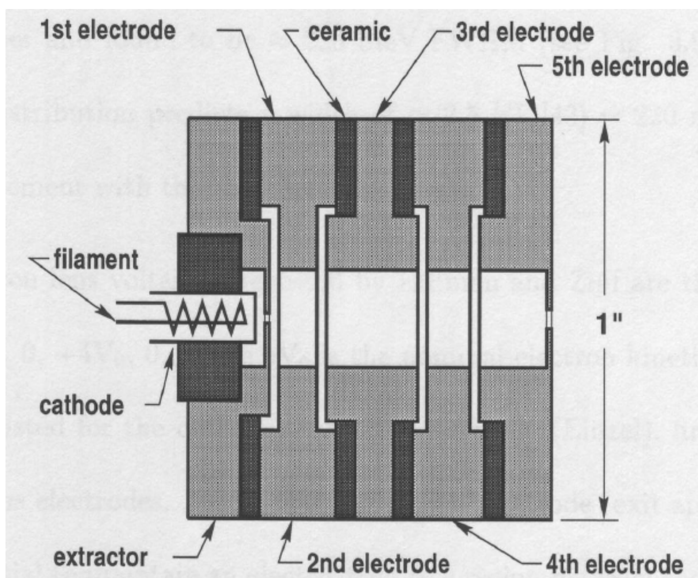



Figure 3.9: Spectrum collected by reflecting the electron beam off a sample and into an MDS-50 (VG Microtech) hemispherical electron analyser. The resolution of the analyser is known to be $\approx$ 140 meV, and modeling both the analyser resolution function and the electron beam energy spread as Gaussians, such that their widths add in quadrature, the electron beam width is $\approx$ 220 meV.

# Erdman-Zipf Electron Gun

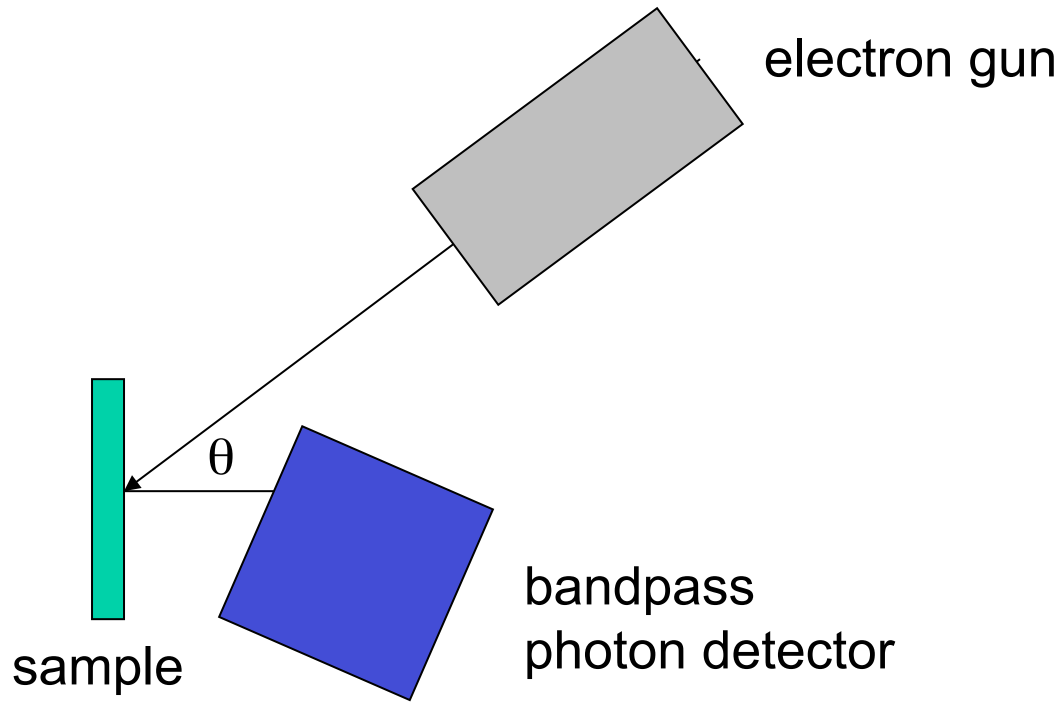




# Isochromat (fixed photon energy) Method

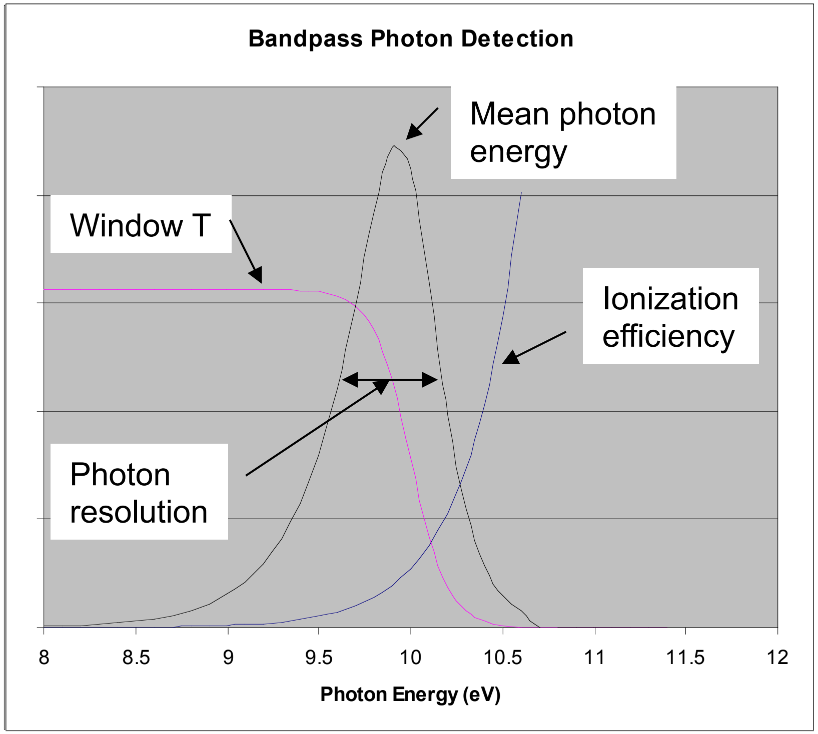
- Fixed photon energy is detected
  - Bandpass detector required
- Incident electron energy is scanned, which simultaneously scans the initial and final states (separated by the detection photon energy)
- Experimental data is the flux of photons detected (photons/s) at each electron energy step
- Trick is designing a bandpass photon detector

# Typical Isochromat IPES Apparatus

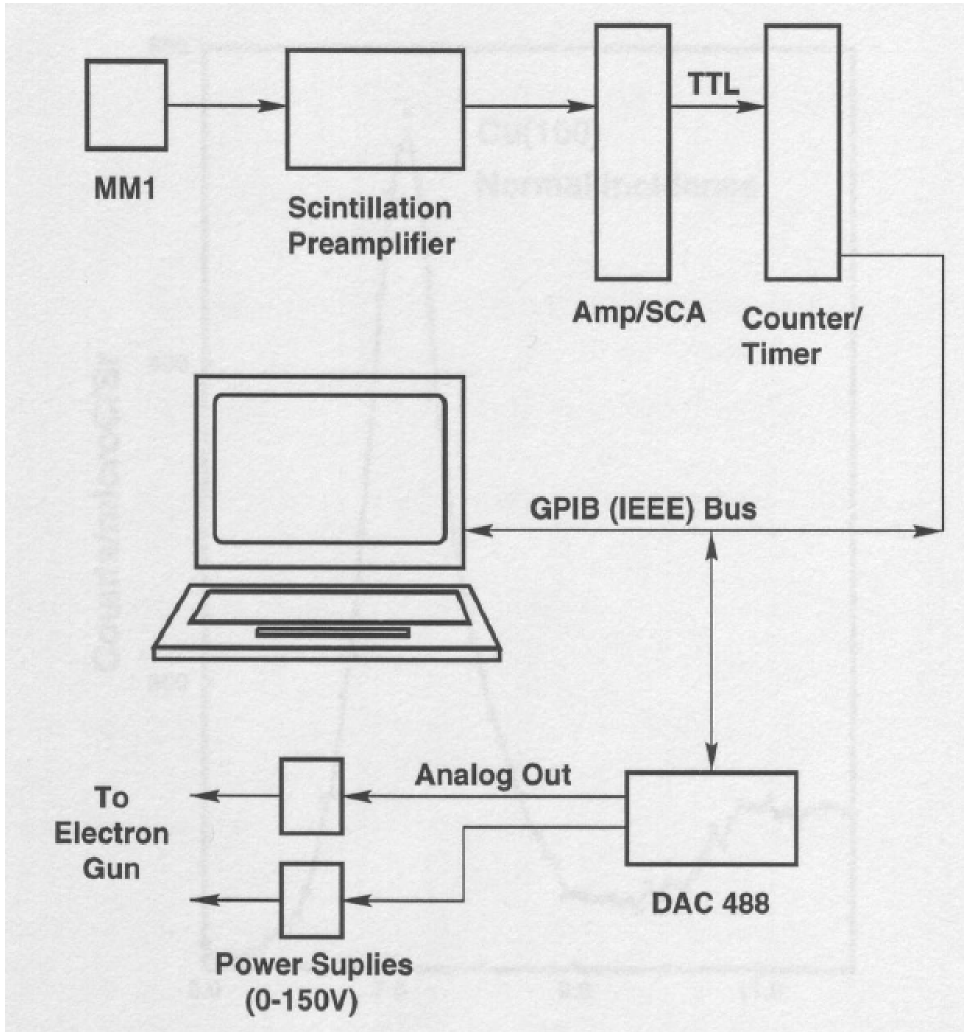


# UV Bandpass Photon Detectors

- Photon liberates an electron through a photoionization process (photoelectric effect or ionization of a gas)
- Detector must have a sharply increasing photoionization efficiency around the photon energy of interest
  - This forms the low energy edge of the bandpass window
- Window with transmission cutting off sharply above the photon energy forms the high energy edge (LiF, $CaF_2$, etc)
- Overall detection function is given by the product of the sensitivity and the window transmission
- Initial detection electron is multiplied (through cascading ionization processes) and electron pulse detected



# Pulse Counting Apparatus



# UV Bandpass Photon Detectors

- Geiger-Mueller tubes (UV window + ionizing gas)
- UV sensitive Photomultiplier + UV window
- Electron multiplier (channeltron, multichannel plate) coated with UV window material

In all cases, overall energy resolution (electron energy and photon detection combined) is between 0.5-0.75 eV

# IPES Resolution: Fermi Edge of Au

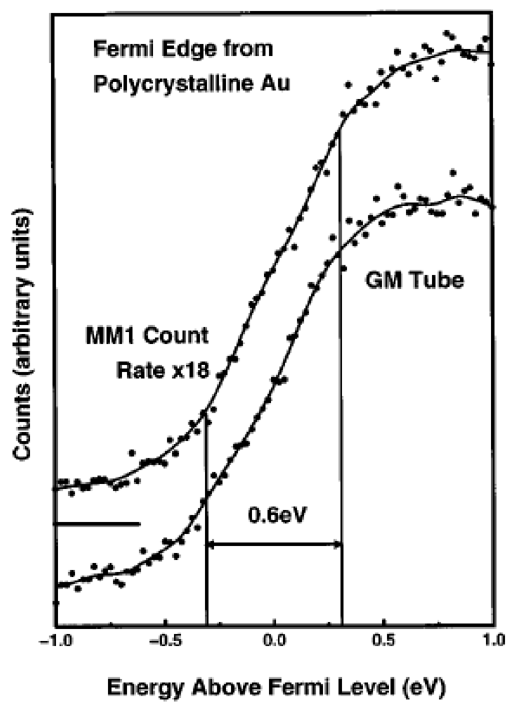



FIG. 3. This figure contains the same spectra as presented in Fig. 2, with the MM1 data multiplied by 18, and shifted vertically. The energy scales of each spectrum have been shifted to align their Fermi levels. The resolution of each detector was estimated to be approximately 0.6 eV. The collection time of the MM1 data was 20 times that of the GM data.

Hill and McLean, Rev Sci Inst, 69, 261, (1998).

# Wavelength Dispersive Methods

- Monoenergetic electron beam incident on sample
- Sample emits photons of various wavelengths, corresponding to different possible transitions
- Photons of different wavelengths are separated using a dispersive device (diffraction grating)
- Photons detected using a position sensitive detector
- Higher resolution, but lower count rate than isochromat mode due to grating loss, larger working distance ($1/r^2$)
- More difficult/expensive to build

# Example: IPES of Cu (100)

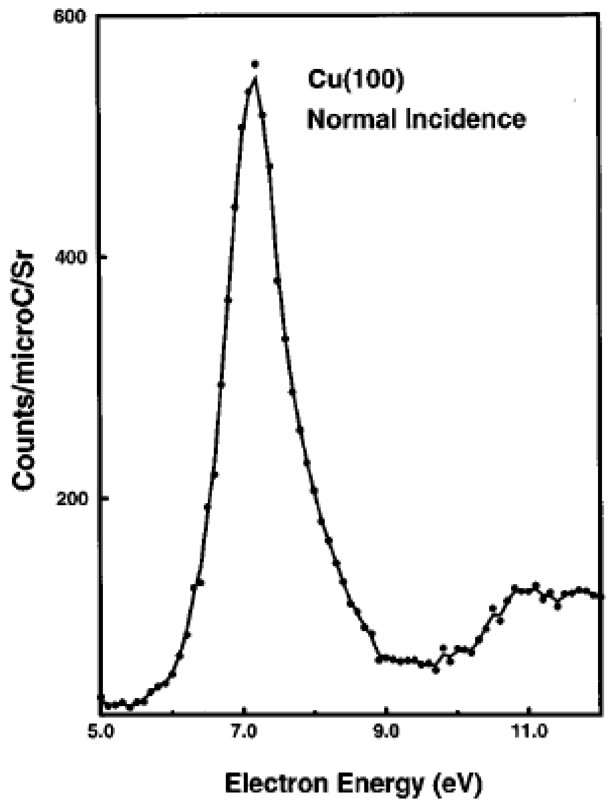



FIG. 1. The above figure shows an inverse photoemission spectrum from Cu (100) at normal incidence, collected using the MM1 detector. It can be directly compared with the data of Schäfer *et al.* (Ref. 11).

Hill and McLean, Rev Sci Inst, 69, 261, (1998).

# Example: IPES of Si(111)-(7x7)

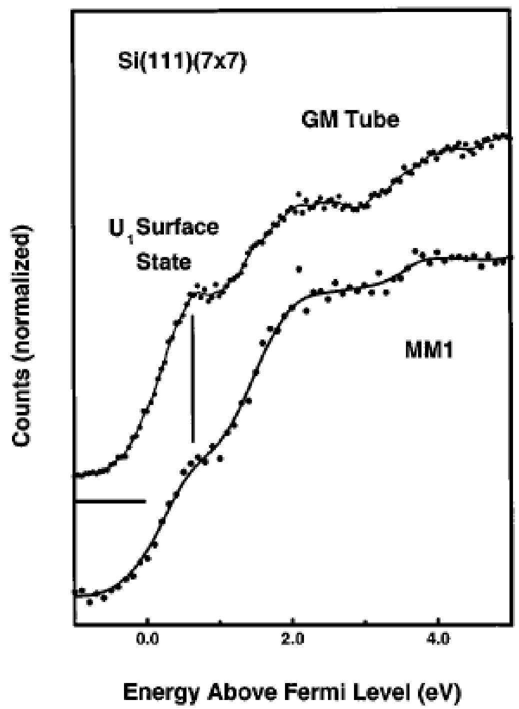
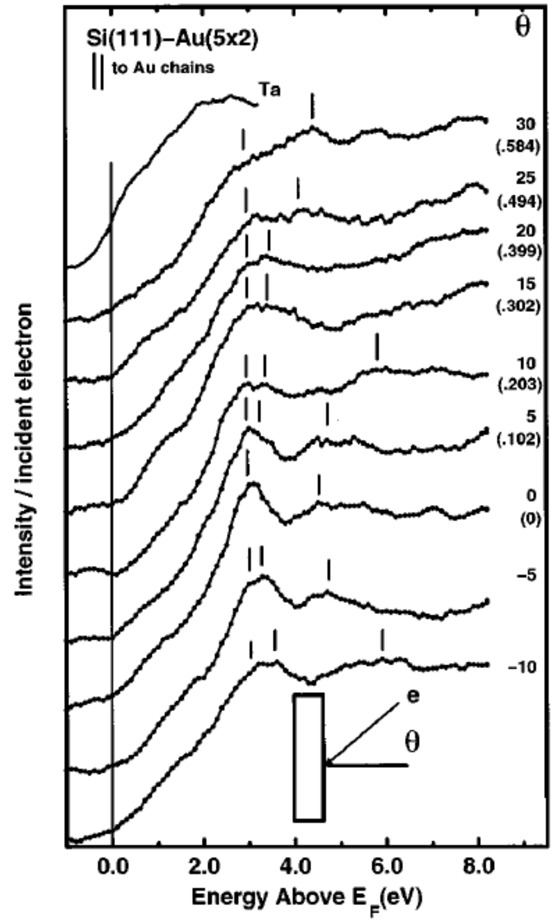



FIG. 4. Inverse photoemission spectra of Si (111) ($7\times7$) from the GM tube (top), and the MM1 detector (bottom). The MM1 data has been smoothed by convolution with a Gaussian width of 0.300 eV full width at half maximum, while the GM spectrum presented is raw data. Notice the improved sharpness of the surface state, $U_1$, in the GM tube spectrum. The state in the MM1 spectrum is washed out by the smoothing process. Each spectrum has been shifted by the difference between its detector's mean photon energy and the electron gun cathode work function, to give the spectral energy relative the Fermi level.

Hill and McLean, Rev Sci Inst, 69, 261, (1998).

# K-Resolved IPES

- Same approach as UPS
  - When the electron crosses the vacuum/surface interface, the component of the momentum parallel to the surface is conserved.
- By varying the angle of the incident electrons with respect to the surface normal, different momentum states are accessed

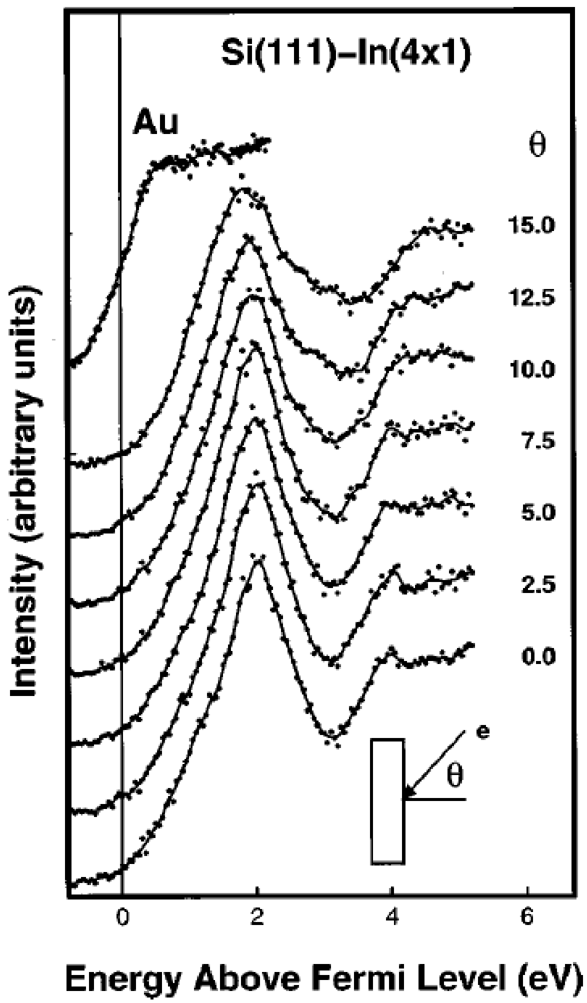



I. G. Hill and A.B. McLean, Phys Rev B, 55, 15664, (1997).

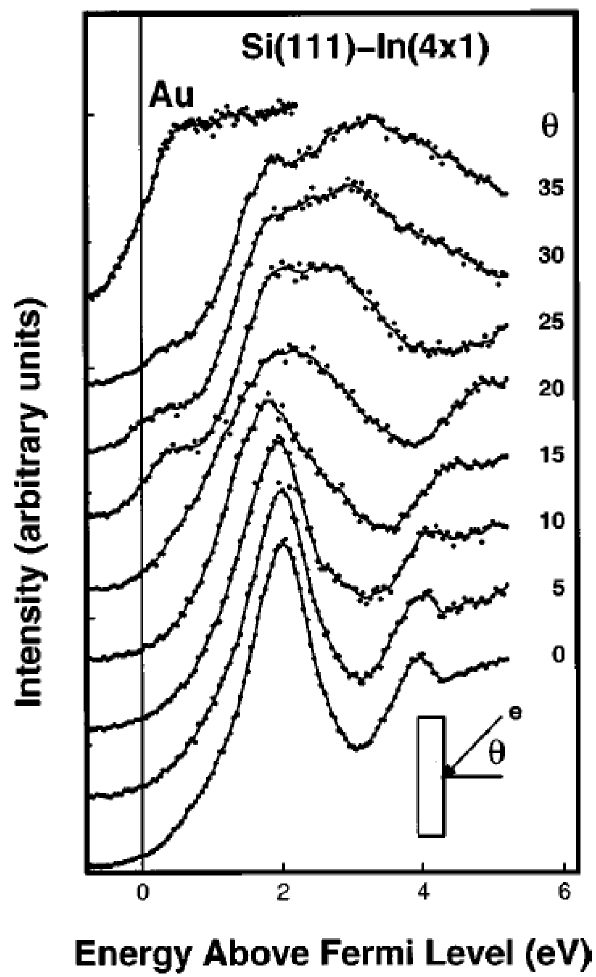
# KRIPES on Si(111)-In(4x1)

In atoms form 1-D chains on Si(111). Electrons are delocalized along the chains, and localized perpendicular to the chains

Perpendicular to Chains

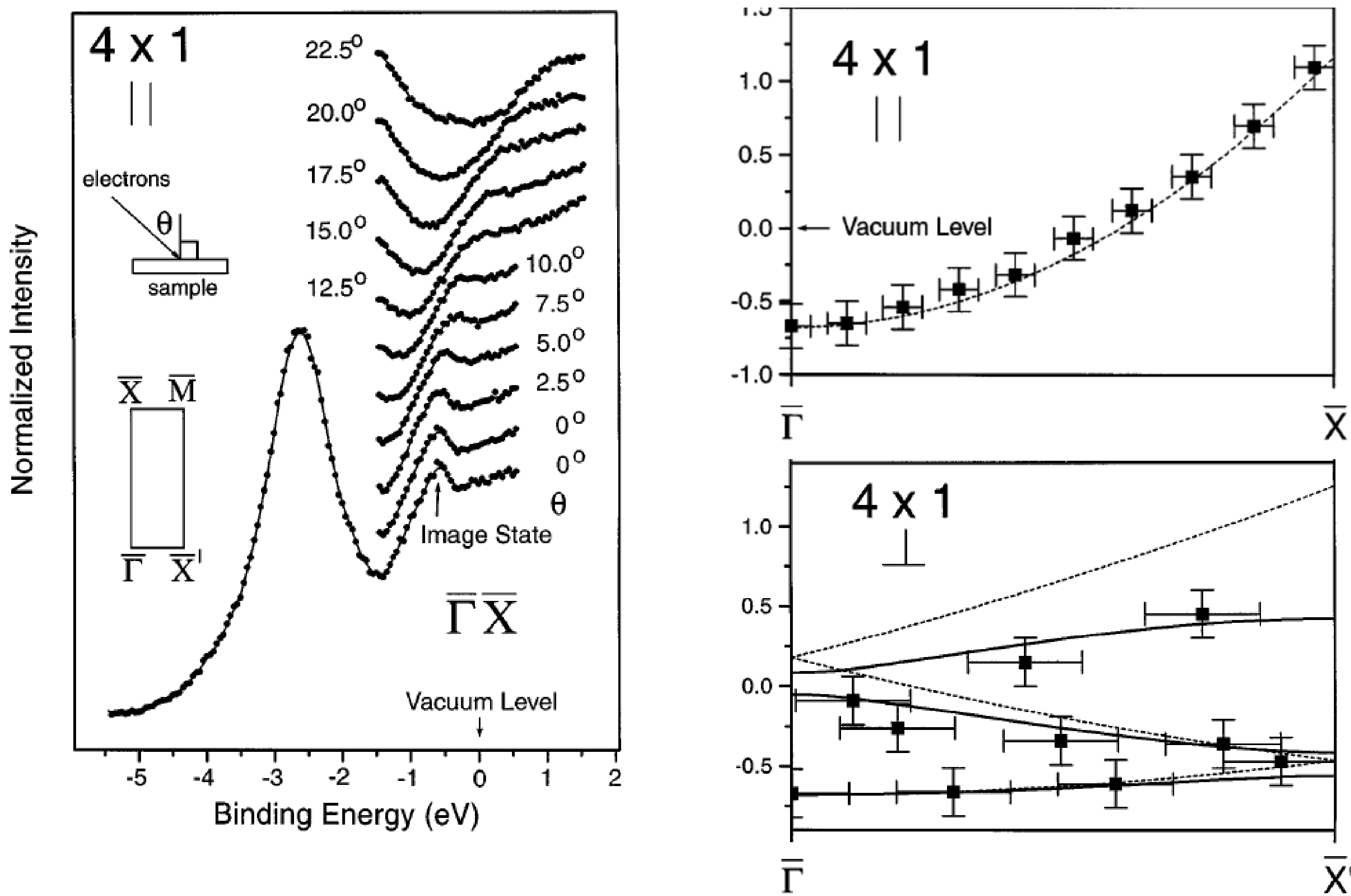



Parallel to Chains




Hill and McLean, Phys Rev B, 56, 15725, (1997).

# I-D Image States




I. G. Hill and A.B. McLean, Phys Rev Lett, 82, 2155, (1999).

# Difficulties of IPES

- Commercial systems not available – must be home built
- Poor energy resolution
- Low count rate due to phase space limitations
  - The density of final states available for an electron or photon with wave vector between k and k+dk:

$$dn \propto 4\pi k^2 dk$$

- Use Golden Rule to estimate the relative cross sections for the photoemission and inverse photoemission processes :

$$\frac{\sigma_{IPES}}{\sigma_{PES}} \approx \frac{dn_{ph}}{dn_{el}} = \frac{k_{ph}^2}{k_{el}^2} = \frac{\left(\dfrac{E_{ph}}{\hbar c}\right)^2}{\dfrac{2mE_{el}}{\hbar^2}} = \frac{E_{ph}^2}{2mc^2 E_{el}}$$

$$\frac{\sigma_{IPES}}{\sigma_{PES}} \approx 1\times 10^{-5} \quad \text{for } \mathrm{E_{ph}} = \mathrm{E_{el}} = 10eV$$