1. STM vs. AFM

a) What is the feedback signal used in STM measurements? And in AFM measurements?

b) Which classes of materials can be investigated by AFM and not by STM? Why?

1. Solution - STM vs. AFM

a)

In STM measurements the feedback signal is the tunneling current between surface and tip. In constant current measurements, a feedback loop keeps the measured current constant and equal to the requested set-point current. In general, this implies that the tip-surface distance (z) changes. This z-signal is used to generate the STM image.

AFM measurements are based on the force between surface and probe.
In contact measurements, the deflection of the cantilever is the signal used as input for the feedback, that is used to keep the probe-sample force constant during scanning. (Note that a constant height mode exists as well).
In non-contact measurements (attractive forces), the probe is set into oscillation. The interaction with the surface modifies the frequency. The force interactions can be determined in two ways: i) by measuring the change in amplitude of the oscillation at a constant frequency just off resonance (amplitude modulation); ii) by measuring the change in resonant frequency directly, using a feedback circuit to always drive the sensor on resonance (frequency modulation).

b)

With AFM one can investigate non-conducting samples, i.e. insulators and intrinsic wide-band gap semiconductors. These materials are not accessible to STM since there are no states at the Fermi level. Therefore it is not possible to obtain a tunneling current at low bias.
Note however that for semiconductors one can obtain a tunneling current using high enough bias, such that the Fermi level of the tip is aligned with the top of the valence band, or with the bottom of the conduction band. This implies the use of high bias (several eV).

2. The surface state of Ag(111)

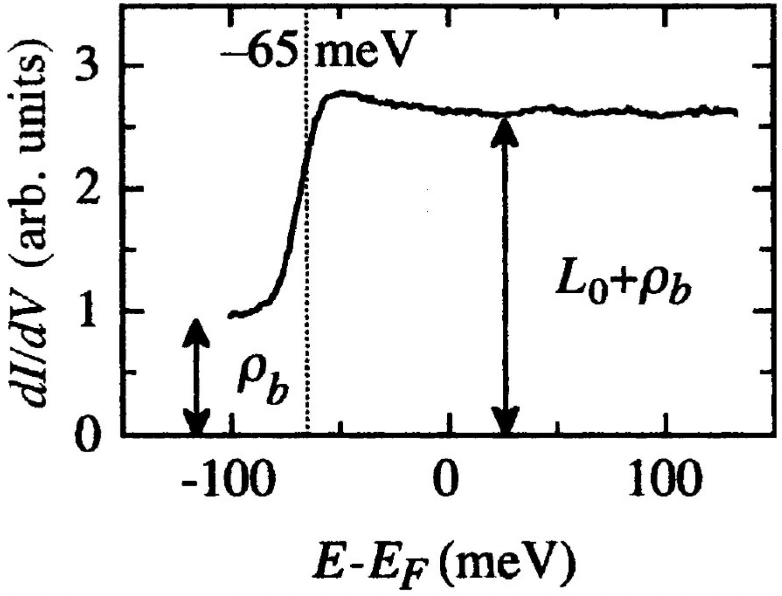
The figure shows a dI/dV spectrum acquired on a Ag(111) surface.

The step observed at $E_0 = -65$ meV corresponds to the onset of the surface state. The surface state is a 2D free-electron gas, as a consequence its DOS is constant, indicated here as $L_0 = m^*/\pi\hbar^2$.

Consider for simplicity that also the bulk DOS ρ_b as well as the tip DOS ρ_t are constant, and that $T = 0$.

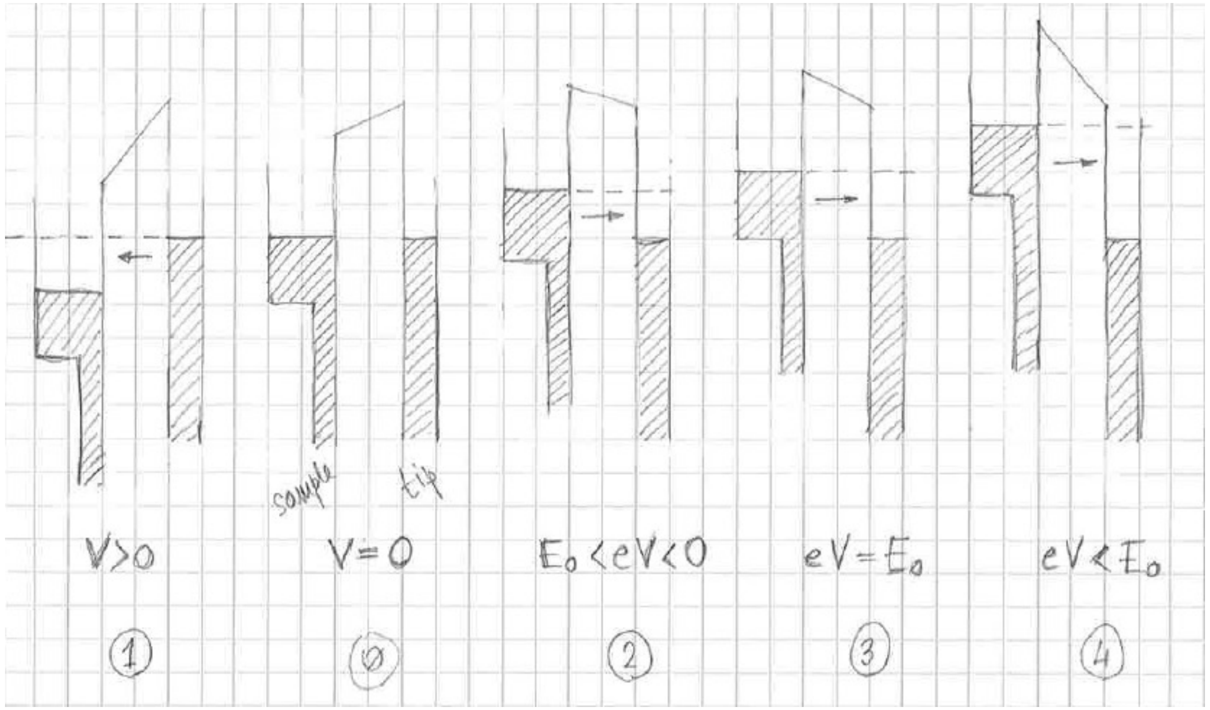
a) Sketch the energy barrier scheme at the relevant bias voltages corresponding to the different regions of the dI/dV spectrum.

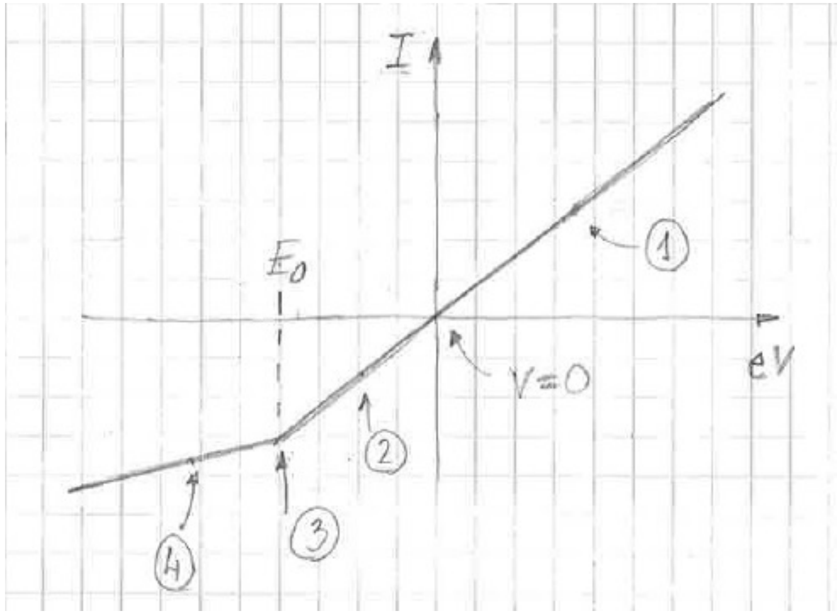
b) Sketch the corresponding current vs bias voltage (I vs V) curve.



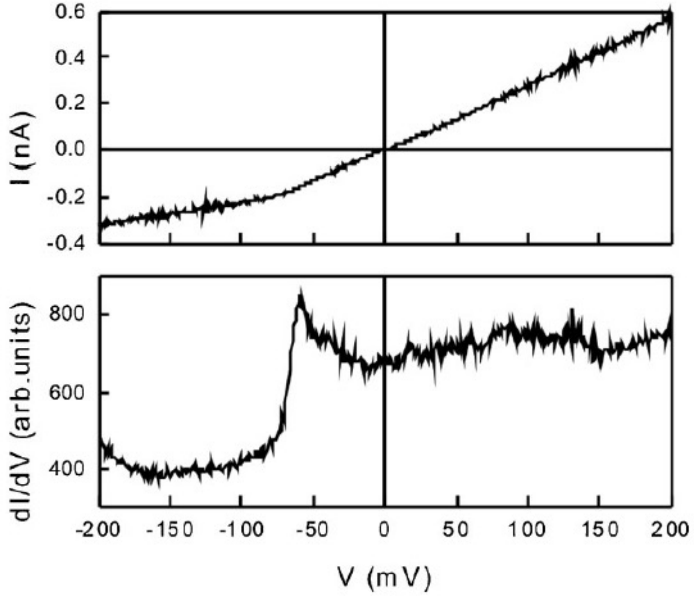
Adapted from
Appl. Phys. A **75**, 141–145 (2002)

2. Solution – The surface state of Ag(111)





The tunneling current is linear with the same slope for all biases where the surface state contributes to the current (1 and 2): constant dI/dV (constant DOS) → linear I. Once the surface state onset energy E_0 is reached (3), the tunneling current continues to increase (in absolute value) but with a smaller slope (4), since the density of states contributing to the current for $eV \; < \; E_0$ is lower.

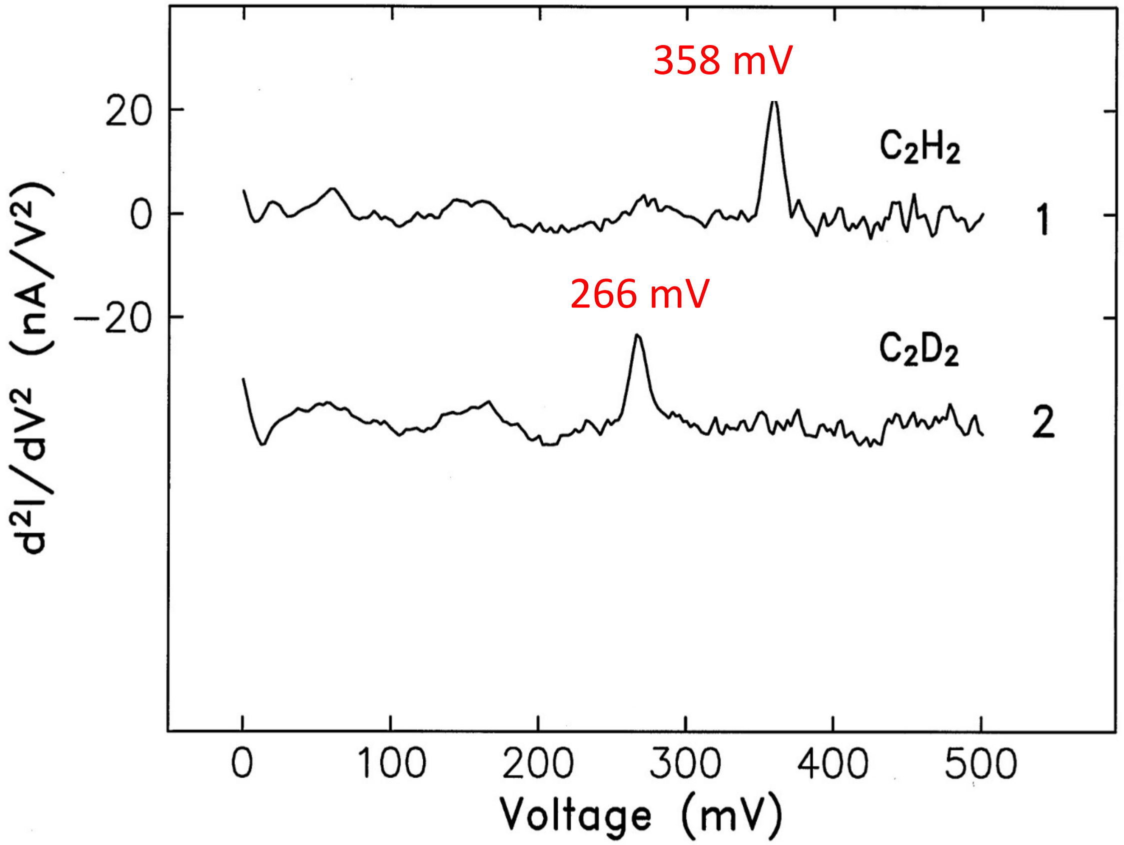


The figure on the left shows a mesurement of the Ag(111) surface state taken from another reference, where both $I(V)$ and dI/dV vs V are presented.

K. Morgenstern et al., Phys. Status Solidi B **250**, 1671 (2013)

3. IETS: Vibrational modes

Verify the scaling of the observed stretching mode when replacing hydrogen with deuterium
(assume the same spring constant K for the C-H and the C-D bonds)



Adapted from :
B. C. Stipe *et al.,* Science **280**, 1732 (1998)
B. C. Stipe, *et al.,* Phys. Rev. Lett **82**, 1724 (1999)

3. Solution – IETS: Vibrational modes

$$\hbar\omega = \hbar\sqrt{\frac{K}{m_{reduced}}}$$

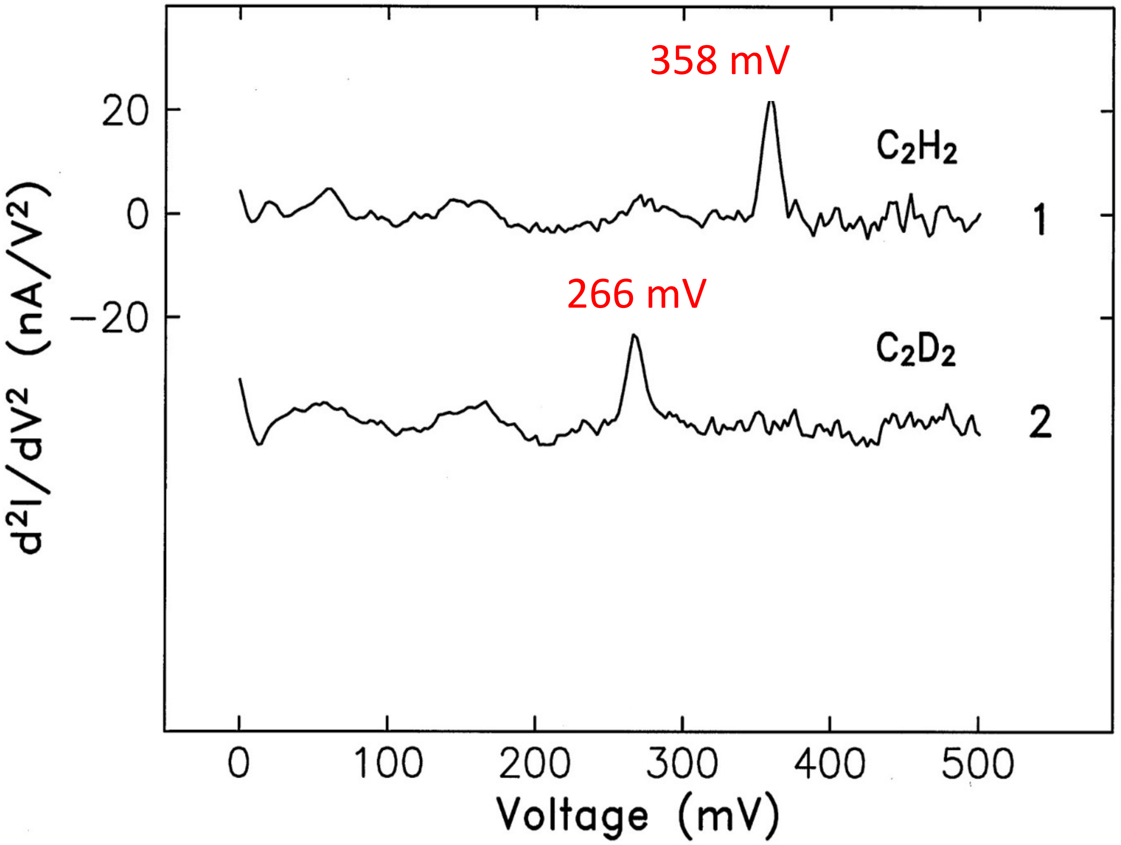
$$\mathrm{C-H}: \frac{1}{m_{\mathrm{CH}}} = \frac{1}{12} + \frac{1}{1} = 1.08 \rightarrow \sqrt{m_{\mathrm{CH}}} \approx 0.96$$

$$\mathrm{C-D}: \frac{1}{m_{\mathrm{CD}}} = \frac{1}{12} + \frac{1}{2} = 0.58 \rightarrow \sqrt{m_{\mathrm{CD}}} \approx 1.31$$

$$\hbar\omega_{\mathrm{CH}} = 358\,\mathrm{meV}$$

$$\hbar\omega_{\mathrm{CD}} = \hbar\omega_{\mathrm{CH}}\frac{\sqrt{m_{\mathrm{CH}}}}{\sqrt{m_{\mathrm{CD}}}} = 262\,\mathrm{meV}$$

in good agreement with the observation



Adapted from :

B. C. Stipe *et al.,* Science **280**, 1732 (1998)
B. C. Stipe, *et al.,* Phys. Rev. Lett **82**, 1724 (1999)