1 Introduction

The scanning tunneling microscope (STM) has revolutionized surface science since its invention in 1982 (Binnig and Rohrer, 1982) by providing a means to directly image atomic scale spatial and electronic structure. Using the combination of a coarse approach and piezoelectric transducers, a sharp, metallic tip is brought into close proximity with the sample. The distance between tip and sample is less than 1 nm, which means that the electron wave functions of tip and sample start to overlap. A bias voltage is applied between tip and sample that causes electrons to tunnel through the barrier. The tunneling current is a quantum mechanical effect: tunneling of electrons can occur between two electrodes separated by a thin insulator or a vacuum gap and the tunneling current decays on the length scale of one atomic radius. The tunneling current is in the range of picoamperes to nanoamperes and is measured with a preamplifier. In an STM, the tip is scanned over the surface and electrons tunnel from the very last atom of the tip apex to single atoms on the surface, providing atomic resolution. The exponential dependence of the tunneling current on the tip–sample distance can be exploited to control the tip–sample distance with high precision. There are four basic operation modes for any STM: constant current imaging, constant height imaging, spectroscopic imaging, and local spectroscopy. Their interpretation and realization will be briefly discussed below. For details about other modes and a comprehensive introduction to electron tunneling and STM see Wiesendanger (1994).

To acquire constant current images, a feedback loop adjusts the height of the tip during scanning so that the tunneling current flowing between tip and sample is kept constant. The height $z$ is adjusted by applying an appropriate voltage $V_z$ to the $z$-piezoelectric drive while the lateral tip position $(x,y)$ is determined by the corresponding voltages applied to the $x$ and $y$ piezoelectric drives. The recorded signal $V_z$ can be translated into a topography $z(x,y)$ if the sensitivity of the piezoelectric drives is known. The word
topography should be used with caution: since the local density of states at the Fermi level is measured, a molecule adsorbed on a metal surface that reduces the local density of states and may actually be imaged as a depression.

To acquire constant height images, the feedback loop is switched off, i.e., the tip is scanned at constant height above the surface, and variations in the current are measured. This mode has the advantage that the finite response time of the feedback loop does not limit the scan speed. It can be used to collect images at video rates, offering the opportunity to observe dynamic processes at surfaces. However, thermal drift limits the time of the experiment and there is an increased risk of crashing the tip.

To measure differential conductance \( (dI/dV) \) maps with the STM, a high-frequency sinusoidal modulation voltage is superimposed on the constant dc bias voltage \( V_{\text{bias}} \) between tip and sample. The modulation frequency is chosen higher than the cutoff frequency of the feedback loop, which keeps the tunneling current constant. By recording the tunneling current modulation, which is in phase with the applied bias voltage modulation, with a lock-in amplifier, a spatially resolved spectroscopic signal \( dI/dV \vert_{V_{\text{bias}}} \) can be obtained simultaneously with the constant current image (Binnig et al., 1985a,b).

By measuring the differential conductance \( dI/dV \) at a fixed tip position with open feedback loop (constant tip–sample distance \( z \)) while sweeping the applied bias voltage, an energy-resolved spectrum can be obtained. This is useful for probing, e.g., band-gap states in semiconductors or the onset of surface states on metals.

The tunneling current \( I \) at a given tip position is approximately equal to the integrated local density of states (ILDOS), integrated over the energy range between the Fermi energy \( E_F \) of the sample and \( eV \), where \( V \) is the applied bias voltage. Therefore the differential conductance \( dI/dV \) is approximately proportional to the local density of states (LDOS) of the sample at the energy \( eV \), and a constant current image should represent a contour of constant ILDOS. For measurements close to \( E_F \), i.e., at low bias voltages, the LDOS and ILDOS are essentially the same and a constant current image at low bias (a few millivolts) is therefore approximately proportional to the sample LDOS at the Fermi energy \( E_F \) (assuming the tip has a uniform density of states and the temperature is low). To illustrate how to arrive at the picture presented above, the theoretical treatment of electron tunneling is briefly outlined.

A one-dimensional WKB approximation predicts that the tunneling current at low temperatures (where the Fermi distribution is a step function) is given by

\[
I = \int_0^{eV} \rho_s(E, x) \rho_t(-eV + E, x) T(E, eV, x) \, dE
\]

(1)

where \( \rho_s(E) \) and \( \rho_t(E) \) are the density of states of the sample and the tip at the location \( x \) and energy \( E \), measured with respect to their individual Fermi levels, and \( V \) is the applied bias voltage (Hamers, 1989). The