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Spin-Polarized Scanning Tunneling Microscopy

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We present an overview of spin-polarized scanning tunneling microscopy (Sp-STM). As in STM, the electron density near the sample surface can be imaged. In addition, Sp-STM allows us to map the spin polarization. Thus, information on the magnetic configuration of the sample surface can be gathered. Three imaging modes are currently being used: the constant-current mode, the spectroscopic mode, and the differential magnetic mode. The principles of the three modes are explained, and their advantages and limitations are discussed in the framework of imaging ferromagnetic and antiferromagnetic surfaces of bulk materials and thin film systems. Further, two approaches for controlling the spin direction of the tip apex, i.e., the sensitive spin component, are discussed. Surface or interface magnetic anisotropies at the tip apex may be used to align the axis of sensitivity or alternatively, the shape anisotropy of the whole tip may determine the spin direction. Finally, it is demonstrated that Sp-STM can be used beyond magnetic imaging. Valuable information on the spin resolved electronic structure or on the fundamental processes of spin-polarized tunneling may be obtained.

1 Introduction

In scanning tunneling microscopy (STM), the electron charge is used to carry information in the imaging process. The small tunneling current between the tip and the conductive surface is used as a feedback parameter to move the tip. During scanning in the constant current mode, the apex of the tip is held on equi-current lines several Å above the sample surface by the current feedback mechanism. In first approximation, i.e., in the Tersoff–Hamann model [1,2], these lines correspond to lines of constant charge density of the sample surface probed by the tip apex. A plot of the $z$-coordinate, i.e., the coordinate perpendicular to the overall sample surface, as a function of the position $x$ and $y$ in the surface plane is therefore called a topographic STM image and reflects the spatial distribution of the density of states of the electrons [3]. In the case of a sharp apex, individual atoms can be resolved in topographic images [4]. In the above picture, the spin of the electron has been neglected. For most materials, this simplification is well justified as the electron...
density does not depend on the spin of the electron. For ferromagnetic or antiferromagnetic materials, however, the density of states is spin-split into majority and minority states. A net spin polarization is present in the atoms and the individual atoms carry a magnetic moment. In spin-polarized STM (Sp-STM) the tip itself is a source of spin-polarized electrons. Information on the spin polarization of the sample surface may be obtained via the spin-dependent tunneling process between tip and sample. In the case that the spin-dependent part of the tunneling current can be separated from the spin-independent part, it is possible to obtain information on the spin- or magnetic configuration of a sample surface with the same lateral resolution as topographic information, i.e., with atomic resolution. Thus, Sp-STM is the magnetic imaging technique with ultimate lateral resolution, which for the first time allows the study of the magnetic configuration of antiferromagnets in real space. Examples for imaging both ferromagnetic and antiferromagnetic surfaces are given, after the principles of spin-polarized tunneling are introduced in detail. Three different approaches to separate spin information from the tunneling current are discussed, and examples are given for all three imaging modes. The potential of the different techniques is illustrated and their advantages and disadvantages are discussed. Further, we focus on tip preparation and finally show that Sp-STM can be used beyond magnetic imaging to learn more about spin-split density of states and the mechanism of spin-polarized tunneling, per se.

1.1 Spin-Polarized Tunneling

The principle of operation of Sp-STM is based on the fundamental property of ferromagnets and antiferromagnets—that their magnetic moment is related to an imbalance in occupation of electrons of different spins. Due to the spin-sensitive exchange interaction, the density of states splits up into minority and majority densities (see Figure 1(a)). The imbalance causes a spin polarization. This is in contrast to paramagnetic substances, where the distributions of spin-up and spin-down electrons are identical and no spin polarization is present. The splitting

![Figure 1](image-url)