Scanning Tunneling Microscopy (STM) and spin-polarized STM

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Contents

1 Introduction

In scanning tunneling microscopy (STM), the electron charge is used as information carrier in the imaging process. The small tunneling current between the tip and the conductive surface is used as a feed back parameter to move the tip and to image the surface with up to atomic resolution.

A brief overview is given on the application of STM in imaging magnetic nanostructures and obtaining information on their shape, size, density, chemical composition etc.

Beyond imaging, STM can also be used to create nanostructures. Examples and methods for this are illustrated and the future prospects are discussed.

Finally, the extension of STM to the electron spin is introduced. Spin-polarized STM allows to additionally map the spin polarization. By this, 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 structures.

2 History, theory and applications of STM

2.1 Early Experiments

The history of the development of STM is shortly given and the experimental set up is introduced [1,2]. The first results showing atomic real space images of conductive surfaces are shown. Since these early experiments, STM has become one of the most powerful surface science tools to investigate surface morphology and atomic configurations.

2.2 Theory of STM

As the STM uses the tunneling current between a metallic tip and a conductive surface to image, it is necessary to answer the question: What do we actually see with an STM?

This question is answered on the basis of the quantum mechanical Bardeen model for tunneling in the Tersoff-Hamann approximation [3,4]. These lead to the simplified picture that an STM sees the electronic density of states of the sample surface.

Examples are given that show the validity but also the limits of this theory.

2.3 STM as a high resolution tool to study magnetic nanostructures

The high resolution of STM allows to characterize magnetic nanostructures with high precision. We give examples of studies that combine STM data on the shape (i.e. dimension) of particles with their magnetic properties [19]. STM may also used as a powerful tool to monitor the growth mode of magnetic films and the intermixing at the interface between a non magnetic substrate and a magnetic film. With this, it offers valuable insight into effects like exchange coupling or magnetic dead layers.

2.4 STM as a tool to atomic control of magnetic clusters

We further demonstrate that STM in combination with classical diffusion theory can be used to stabilize atomic clusters of magnetic elements. In combination with spatially averaging techniques, this allows to extract information on the spin-orbit interaction in very small clusters.

2.5 Atomic manipulation with STM

We give an overview on procedures to use the tip sample interaction to move atoms on a surface in a controlled way. This allows to build nanostructures atom by atom and in a second stage, characterize the interaction of these atoms. The Kondo effect and quantum corrals will be discussed [20].

3 Spin-polarized STM

We briefly introduce two experimental approaches to Sp-STM: the use of optically pumped GaAs tips [7] and the use of ferromagnetic or antiferromagnetic tips. Both ways lead to a spin polarization of the tip states that in turn changes the tunneling probabilities depending on the spin polarization of the sample surface.

3.1 Theory of Sp-STM or spin-polarized tunneling

The tunneling current in Sp-STM depends not only on the tip-sample separation but also on the relative orientation between the tip and sample spin polarization. This way, spin information is transformed to a measurable tunneling current. On basis of the Jullière model [5], three different imaging modes [6,8] are introduced and the specific tip preparation methods are given.

3.2 The constant current mode

In the constant current mode of Sp-STM, a spin-polarized tip is scanned over a spin-polarized surface in the conventional constant current mode of STM. In this case, the images contain mixed topographic and spin information. On top of the topographic contrast you find a minute topographic variation related to the spin [9]. We show the advantages but also the limits of this approach and give a perspective, how to separate magnetic and topographic information [10].

3.3 The spectroscopic mode

A mode that under certain circumstances allows to separate topographic information from spin information is spin-polarized scanning tunneling spectroscopy [11,12]. In this mode, tunneling spectra are taken with a spin-polarized tip. The spectra vary as function of the relative orientation of sample and tip spin polarization. We demonstrate, how this mode can be used to characterize magnetic nanostructures. The advantages and disadvantages of this mode are given.

3.4 The differential magnetic mode

In the differential magnetic imaging mode, the tip magnetization is modulated to strictly separate the spin information of a sample surface from the topography [13]. The reversal of the tip magnetization causes changes in the tunneling current. By measuring the difference of the current for two magnetic configurations of the tip, the spin information can always be separated from the topography. This mode is especially suited for complex spin structure or for systems with inhomogeneous density of states. The disadvantages and the merits of the approach are compared to the other operation modes.

4 Sp-STM beyond magnetism

In the last section, we show how Sp-STM can be used to learn more about the tunneling process itself and secondary processes involved in tunneling. We show the limits of the Tersoff-Hamman model and briefly introduce ballistic tunneling theory [14]. We show that not only the density of states but also the band structure of the sample is important. Further, we demonstrate that Sp-STM can be used to learn about inelastic tunneling processes like magnon scattering.

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