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Probing surface magnetism with ion beams

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Abstract

Ion beams can be used to probe magnetic properties of surfaces by a variety of different methods. Important features of these methods are related to trajectories of atomic projectiles scattered from the surface of a solid target and to the electronic interaction mechanisms in the surface region. Both items provide under specific conditions a high sensitivity for the detection of magnetic properties in the region at the topmost layer of surface atoms. This holds in particular for scattering under planar surface channeling conditions, where under grazing impact atoms or ions are reflected specularly from the surface without penetration into the subsurface region. Two different types of methods are employed based on the detection of the spin polarization of emitted or captured electrons and on spin blocking effects for capture into atomic terms. These techniques allow one to probe the long range and short range magnetic order in the surface region.

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1. Introduction

Magnetic phenomena play an important role for a variety of technological applications as, e.g. sensors, data storage, or permanent magnets. As a consequence, a fundamental understanding of magnetic order in solids is a key issue in basic research on this topic. The understanding of magnetism can be achieved only from quantum mechanical treatments where complex exchange and correlation effects play a dominant role. In recent years it was revealed that structures of reduced dimensions, in particular thin films, show fairly spectacular properties which are absent in devices of larger scale. A prominent example is the giant magneto-resistance (GMR) effect [1,2] which was discovered in the late 1980s and is nowadays the basis of reading heads for magnetic storage on hard disk drives. This component can be considered of an early realization of a "spintronic" device where in addition to the flow of electronic charge – used in conventional electronics – the electronic spins play an essential role. Non volatile magnetic RAMs (MRAM) or spin transistors are discussed as future powerful spin electronic components.

For the design and development of spintronic devices a detailed understanding of the fundamental mechanisms is needed. This means that the relevant interactions of spins in materials with different magnetic properties have to be understood. Substantial progress in recent years has been achieved in the understanding of coupling phenomena between layers with long range magnetic order separated by non magnetic spacer layers. It turns out that spin interactions at the interfaces play a decisive role for understanding the resulting magneto-resistance effects. Concerning basic research on this topic, experimental methods have to be applied which are particularly sensitive to magnetic properties of ultrathin films and topmost layers of interfaces.

In this paper we will review in a concise manner the potential to make use of fast ion beams for studies on magnetic order at surfaces. The discussion will focus on methods which show a high sensitivity to relevant magnetic

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properties in the surface region. It turns out that ion beam probes provide powerful experimental tools which allow one to study the long and short range magnetic order of surfaces and ultrathin films. Intrinsic features of atomic probes, i.e. trajectories of probing atoms or ions as well as electronic transfer processes between solid and atomic projectiles, result in an extreme sensitivity of experimental methods based on ion beams to the vacuum solid interface. The conceptual principle of the various available methods are in general simple to understand, the detailed analysis towards a quantitative modelling of the processes, however, is an intricate task. Various aspects on the electronic interaction mechanisms have still to be cleared up before the power of methods based on ion beam scattering can be exploited in an appropriate manner. This latter aspect has led to some misinterpretations and controversies over the years and will be discussed and commented in view of the current understanding of the relevant interaction mechanisms.

2. Concepts of studies on surface magnetic using ion beams

Among the different methods to study the magnetism of surfaces and thin solid films, techniques using ion beams have interesting features. We will discuss below a number of experiments which demonstrate the high sensitivity of ion probes to the region at the interface. In this respect, ion beams provide ideal properties for studies on surface magnetism and have significantly smaller probing depth at surfaces compared to, e.g. the established magneto optical Kerr effect ("MOKE") where the probing depth is given by the penetration of light into the solid. The methods for studies on the magnetic order at surfaces are based on two different concepts:

(1) Ion induced emission of spin polarized electrons and the subsequent analysis of the spin polarization of the electrons ejected to vacuum [3]. Depending on the impact geometry of the ions with respect to the surface this technique is fairly sensitive to the near surface region. Even for large angle impact of ions with energies larger than typically keV the probing depth is given by the escape and transport length of electrons in metals which are of the order of 1 nm.

(2) Capture of spin polarized electrons into terms of atoms or ions during scattering from the surface of the magnetized sample [4,5]. The spin polarization of the ensemble of captured electrons affects the capture itself or the evolution of the resulting atomic state in a specific manner. Two different concepts have been used so far to monitor the electronic spin polarization and the surface magnetic order:

   (a) Coupling of angular momenta in the atom via fine and/or hyperfine interactions results in an anisotropy transfer from the electronic spin system to the ensemble of orbital angular momenta and nuclear spins. It is evident that this concept works only for non-zero orbital angular momenta and nuclear spins. Based on the coupling of quantum mechanical angular momenta it is straightforward to calculate the anisotropy transfer within the atomic ensemble [6]. However, the information on the spin polarization is not simply related to the spin polarization and the magnetic order of the sample. The atomic spin polarization results from an intricate capture process with specific properties concerning the weighting of initial electronic states from the density of states of the target sample. The quantitative atomic polarization owing to capture of spin polarized electrons can be obtained from the polarization for the ensemble of nuclear spins derived from the anisotropic angular distribution of products after a nuclear reaction [4,7]. The spin polarization can be also probed via the anisotropy transfer to orbital angular momenta which can be detected from the emission of polarized light in the radiative decay of excited atomic terms [5,6].

   (b) In the capture process the formation of atomic multiplet terms is affected by the Pauli exclusion principle. Then only electrons with a specific spin orientation can be captured, whereas for the opposite spin direction electron transfer is suppressed ("Pauli blocking"). As an example we mention the formation of negative hydrogen ions in an open shell 1s1s′ ^{1}S ground term where electrons with opposite orientation of the spins have to be captured [8]. For a highly spin polarized ensemble of electrons with parallel orientation of spins the formation of triplet terms is favoured, whereas the transfer of electrons to the singlet ground term with antiparallel spins is suppressed. The reduction of capture rates is directly related to the spin polarization of the electronic ensemble; for a complete spin polarization no capture into singlet terms can take place.

As an example for the description of the long range ferromagnetic order in the surface region, we show in Fig. 1 the density of states for a seven layer Ni(001) film calculated using density functional theory by Wimmer et al. [9]. The densities of states are given in the left panels for majority (parallel orientation to external magnetic field) and in the right panels for minority (antiparallel orientation) spins for different positions within the films and in vacuum (2.35 a.u. in front of surface layer). The vertical line at a binding energy of about 5 eV (work function) denotes the position of the Fermi level. The data reveals small but defined exchange splittings and different density of states (DOS) within and in front of the thin film. A striking feature is a pronounced difference for the DOS at the Fermi level within and outside of the film. Defining the spin polarization of electrons from the energy dependent DOS