POLARIZED ELECTRONS IN SURFACE PHYSICS

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World Scientific

Published by

World Scientific Publishing Co. Pte. Ltd.
P. O. Box 128, Farrer Road, Singapore 9128

Library of Congress Cataloging-in-Publication Data is available.

Polarized Electrons in Surface Physics

ISBN 9971-978-49-0
9971-978-50-4 pbk

Printed in Singapore by Kim Hup Lee Printing Co. Pte. Ltd.

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Foreword

Surface physics, dealing with physical (and thence also chemical) properties and processes related to the solid/vacuum boundary, has developed into a vast field of still growing scientific and technological importance. (An extensive survey and references may be found in four volumes recently edited by King and Woodruff (1981-1984)). Electrons are essential for surface physics in two respects: firstly, bound electrons are a constituent part of any surface system, essential not only for the very existence of the system (its local bonding and geometry), but also for its vibrational, magnetic and chemical properties; secondly, free electrons provide - in a wide variety of scattering and emission techniques - powerful means of studying surface properties. Particularly interesting and useful phenomena occur, if the ensemble of electrons under consideration is polarized, i.e. if the number of electrons with spin parallel to a preferential direction differs from the number with spin antiparallel. For electrons bound to the surface system, this is associated with ferro- or ferrimagnetic ordering. In electron spectroscopy techniques, one is dealing with a beam of polarized electrons which is incident on the surface or emerges from it. (A general introduction to polarized free electrons and their use in atomic, solid state and high-energy physics is given in a monograph by Kessler (1976 and, updated, 1985)). Interacting with the surface system via exchange or spin-orbit coupling, polarized electron beams have - due to substantial advances in producing them ("sources") and analysing their spin polarization ("detectors") - within the past decade established themselves as a unique tool for studying magnetic, electronic and even geometrical surface properties.

In view of the achievements already made, the rapidly growing interest in and the future promise of this field, the time appears ripe for a comprehensive presentation, which initiates the non-specialist (with a general physics background at the graduate level) and reviews the current state of the art. This is the aim of the present book. It consists of a coherent sequence of fourteen chapters written by top level experts, who have significantly promoted progress in the respective sub-areas of the field.

The book is organized in two main parts: (I) theoretical foundation, (II) experiments and (experimental and theoretical) results.

Part I (Chapters 1 to 4) introduces fundamental concepts and theoretical approaches. Chapter 1 is devoted to the electronic and magnetic structure of clean and adsorbate-covered surfaces at temperatures well below their ferromagnetic transition temperature. After setting the theoretical framework of local spin-density-functional formalism and thin film approximation, the currently most fruitful first-principles theory for calculating the spin-polarized electronic ground state is introduced, and numerical results for a variety of typical transition metal surfaces and overlayers are presented and discussed. While ferromagnetism of the infinite solid ("bulk") at low temperatures is well understood (in particular itinerant Stoner model for 3d transition metals and Heisenberg Model for rare-earth systems) (cf. standard textbooks on Solid State Physics, e.g. Ashcroft and Mermin (1976), Callaway (1976), Harrison (1970)), transition metal ferromagnetism near the Curie temperature is a subject of very recent controversy and progress. Since an understanding of the "bulk" is a prerequisite for understanding the surface, and since polarized electrons (in photoemission) have provided valuable new insight, key concepts (spin fluctuations, local moments, short-range magnetic order) and theoretical state of the art are therefore included in the present book (Chapter 2). This is naturally followed by a survey of surface ferromagnetism near the Curie temperature (Chapter 3), i.e. "critical behaviour", including scaling theory, renormalization group and Monte Carlo simulations. Chapters 1 to 3 having dealt with the spin-polarized (ferromagnetic) structure of surface systems "by themselves", Chapter 4 addresses the interaction of polarized free electrons with magnetic and non-magnetic surface systems (semi-infinite solid with clean or adsorbate-covered surface), whicn is fundamental to a wide variety of electron scattering and emission techniques for investigating surface properties. Observable spin polarization effects may arise from ferromagnetic exchange interaction and/or from spin-orbit coupling, which are both formally incorporated in a one-electron Dirac Hamiltonian containing an effective magnetic field. The theory of elastic spin-polarized low-energy electron diffraction (LEED) is presented in some detail, firstly because of its intrinsic importance and secondly because the "LEED state" (or its time reverse) is an essential ingredient for quantitative theories of other methods like photoemission, inverse photoemission and inelastic electron scattering, which are subsequently discussed. General results due to symmetry properties are presented, and principles of deducing, with the aid of theory, surface properties from experimental data are explained.

Part II (Chapters 5 to 14) deals with experimental techniques, experimental results and physical information obtained by comparing experimental data with their theoretical counterparts. Chapter 5 introduces the essential experimental tools: sources of polarized electrons, spin polarization detectors (polarimeters), synchrotron radiation (linearly and circularly polarized) and photon detectors. Elastic spin-polarized low-energy electron diffraction is presented for non-magnetic and for ferromagnetic surfaces in Chapters 6 and 7, respectively. In particular, the determination of the surface geometry, of the layer-dependent-magnetization at low temperatures and of the ferromagnetic critical behaviour of surfaces is illustrated. The subsequent two Chapters are devoted to spin-dependent electron-electron collision processes. The techniques, which are presented, include in particular high-resolution electron energy loss spectroscopy from ferromagnets, culminating in a "triple scattering" experiment involving both a polarized primary beam and spin analysis of inelastically scattered electrons (Chapter 8), and secondary electron emission (especially Auger emission and the very-low-energy "cascade") (Chapter 9). In addition to revealing details of the electron-electron interaction and ferromagnetic surface and bulk properties, these studies have led to the technologically important development of a magnetic scanning electron microscope. Chapters 10 to 12 are devoted to spin-resolved photoemission due to radiation in the (vacuum) ultraviolet range (photon energies up to about 70 eV). Chapter 10 focuses on semiconductor surfaces, for which spin-orbit coupling together with circular light polarization produces highly polarized photoelectrons, which carry information on the bulk band structure, on doping with impurities and - due to a most recently discovered spin precession effect in non-centrosymmetric crystals - on the spatial extent of the band-bending region near the surface. For non-magnetic metal surfaces, spin-, angle- and energy-resolved photoemission experiments performed with circularly polarized ultraviolet synchrotron radiation permit a direct observation of the symmetry types of the occupied states and promise detailed information on the electronic structure of adsorbed overlayers (Chapter 11). For ferromagnets (Chapter 12), spin-resolved photoemission by linearly polarized or unpolarized light reveals the majority- and minority-spin (quasi-particle) bulk and surface band structures. While photoemission observes the occupied electronic states, its inverse, bremsstrahlung induced by polarized electrons (Chapter 13), provides complementary information on the unoccupied states (in particular in the vicinity of the Fermi level). The retrieval of physical information from experimental photoemission and bremsstrahlung data by means of theoretical model calculations is illustrated in Chapter 14 for ferromagnetic Fe and Ni. In particular, the determination of short-range magnetic order near the Curie temperature is demonstrated, and some light is shed on the influence of chemisorption on surface magnetism. The final Chapter 15 gives a synopsis and an outlook on future prospects for polarized electrons both in fundamental surface physics research and in technological applications.

The organization of Part II is such that physical properties of specific materials are presented in conjunction with the polarized-electron method by which they were revealed. An alternative classification of the results according to materials is indicated in the following "cross reference" table, which may also serve as a Reader's guide to Chapters 6 to 14.

Method \ Material	ferromagnetic metals 3d	ferromagnetic metals 4f	ferromagnetic non-metals	non-magnetic metals	non-magnetic semi-conductors
elastic scattering	7	7		6	
inelastic scattering	8	8		8	
secondary emission	9		9	9	
photoemission	12,14	12	12	11	10
bremsstrahlung	13,14				

Table: Chapters, in which results for different types of material as obtained by polarized-electron methods are presented.

Having outlined the scope and contents of the present book, it seems pertinent to briefly mention some related methods for studying ferromagnetic surfaces, which have not been included. About a decade ago, a substantial research effort was devoted to field emission, i.e. to extracting polarized electrons from ferromagnets by applying a strong electric field (for reviews and references cf. Kessler 1976 and 1985, Campagna et al. 1976, Feuchtwang et al. 1978, Celotta and Pierce 1980). The development of spin-, angle- and energy-resolved photoemission (cf. Chapters 10-12) has, however, superseded field emission as a magnetic surface diagnostic technique, and the polarized-electron source based on field emission from an EuS-coated W tip has - despite its merits of about 90 % polarization and high brightness - not survived in the competition against the presently most widely used and even commercially available GaAs-photoemission source (cf. Chapter 5). Polarized field emission has therefore - to our knowledge -

not been pursued further since about 1980, and belongs to the history of surface physics.

Since we concentrate on techniques involving free polarized electrons, tunneling between superconductors and ferromagnets (cf. e.g. Tedrow et al 1982, Feuchtwang et al. 1978), which yields information on the spin polarization of electron states very close to the Fermi energy, has not been included. For the same reason, Mössbauer spectroscopy (cf. review by Keune 1985) is not represented nor is another interesting nuclear-physics method known as "Electron Capture Spectroscopy" (cf. review by Rau 1982) , in which deuterons impinging at grazing angles on a ferromagnetic surface pick up conduction electrons and thus carry information on surface magnetism. Another recent technique, which yet has to prove its quantitative merits, employs a polarized beam of low-energy positrons and measures the spin dependence of the positronium formation rate at the magnetic surface (Gidley et al. 1982) (cf. also a monograph on positron studies: ed. Mills and Canter 1985). Further, an atomic-physics method, in which spin-polarized metastable atoms are ionized at a ferromagnetic surface and subsequently neutralized in a polarization-dependent conduction-band Auger process, appears promising (Onnelion et al. 1984).

In conclusion of this Foreword, may we express a personal thought? The authors hope that the book is not only useful and enjoyable to you, dear Reader, but that you may also share some of their enthusiasm about this flourishing area of surface physics.

Roland Feder

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