A New Surface Microscope For Magnetic Imaging

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Abstract **---The design concepts and operation of a new type of electron microscope which allows the imaging of magnetic surface structures with high vertical and moderate lateral resolution are discussed. The compact UHV design is based on the use of polarized low energy electrons from a new multidirectional spin gun. Three and six monolayer thick epitaxial cobalt deposits grown in-situ on W(110) have been used as test samples.**

INTRODUCTION

A few years ago SPLEEM (Spin Polarized Low Energy Electron Microscopy) was born by replacing the standard field emission electron source of the original LEEM instrument [1] with a spin polarized source of the Pierce type [2]. Good lateral image resolution which is comparable to SEMPA (Secondary Electron Microscopy with Polarization Analysis), excellent vertical -atomic step - resolution, video rate time resolution and structural information in the LEEM/LEED (Low Energy Electron Diffraction) mode were obtained in addition to magnetic information via difference imaging [3].

The SPLEEM1 imaging approach was applied to a number of problems of interest to surface and interface magnetism by preparing and analyzing the domain microstructures of magnetic islands and magnetic single- and multilayers [4-6]. However, some limitations were inherent in this initial experimental approach such as in-plane magnetization sensitivity only, extreme sensitivity to outside magnetic fields, limited sample preparation and treatment facilities (due mainly to the high sample potential of about 15 kV during microscopy), and the space needs for a large dedicated microscope system.

MICROSCOPE CONCEPTS

The new microscope design and construction concept (SPLEEM2) [7] effectively transfers the dedicated SPLEEM1 microscope system into a flange-on UHV system component with built-in magnetic shielding wherever possible. SPLEEM2 attaches to a standard UHV chamber via a 6" flange and interfaces with a flexible sample exchange and transfer mechanism that can move the sample between the microscope integrated sample stage and the preparation/sample exchange chamber. The relatively small and compact size of the microscope is primarily a consequence of a different way of dividing the ingoing (illuminating) and outgoing (imaging) electron beams of this reflection-type surface microscope. Instead of twice deflecting the electron beam by 60° as in SPLEEM1, the beam is now deflected four times by 45° (see Fig.1). This results not only in a space saving parallel arrangement

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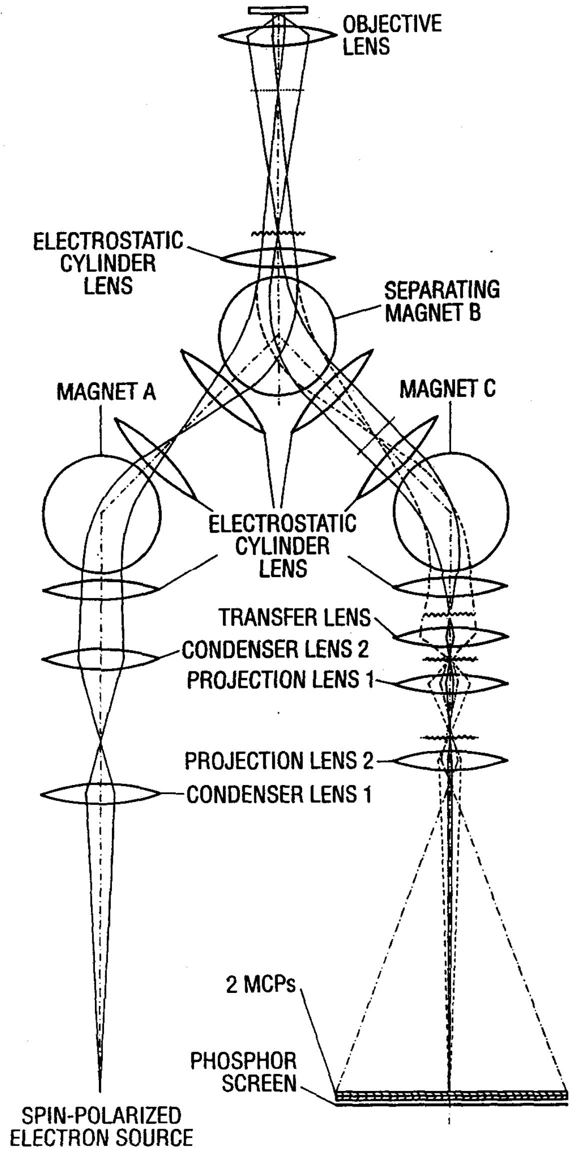

Fig. 1. Electron optical schematic diagram of new microscope design. Refer to text for details.

of the illuminating and imaging microscope columns but was also essential for maintaining the now variable polarization direction of the illuminating electrons by subjecting them to two opposite magnetic deflections.

The electron optical concept can be seen in the schematic beam diagram of Fig.1. The polarized electron source is demagnified by the first condenser lens and then imaged by the combined action of condenser lens 2 and beam deflector A (magnet A and two electrostatic cylinder lenses to provide focusing in two perpendicular directions) and beam deflector B (magnet B and its two cylinder lenses) into the back focal plane of the immersion objective lens. This causes the sample to be illuminated with an almost parallel and coherent beam of electrons with a spot size determined by the electron optical parameters of all elements of the illumination system. The reflected primary electrons form a diffraction pattern in the objective focal plane and the first sample image is formed closer to beam deflector B. The combined action of beam deflector B and C will form a 1:1 reproduction of the first sample image in front of the transfer lens. The focal length of this lens can be adjusted to either transfer the sample image or the diffraction pattern between deflectors B and C into the object plane of the projection lens system for final imaging onto the channel plate image intensifier. Different combinations of projection lens settings then result in a useful magnification range corresponding to fields of view ranging from 40 microns to 2 microns.

It is important to note that in the present design both the sample and the cathode can be kept near ground potential while the average microscope potential is 3-5 kV. The first electrode of the tetrode objective lens is at 15-20 kV resulting in a theoretical lateral image resolution of 9 nm at 2 eV electron energy. This potential distribution results in a much simpler sample stage and spin gun design than in SPLEEM1.

The new multidirectional spin gun is again based on a laser excited GaAs photocathode that is activated by Cs/O_2 cycling [2] and delivers polarization efficiencies of the order of 25% only. (Strained lattice photocathodes with polarizations reaching 80% [8] will be tested in the future). The compact gun design [9] shown schematically in Fig. 2 features a 90° sector and two magnetic lenses as spin rotator elements. The θ-rotating sector is combined with the electrostatic 90° deflector to tilt the electron spin from parallel to the beam axis (θ=0°, i.e. pure magnetic deflection) to θ=90° (pure electrostatic deflection). This is essential for detecting out-of-plane magnitized sample structures. The ϕ rotating magnetic lens is located at the gun exit and has its magnetic field pointing in the direction of the microscope axis. This lens can rotate the illuminating electron spin by ±180° in the plane of the sample.

Samples can be treated or prepared either *in-situ*, i.e. while in the microscopy position, or *ex-situ* for which the sample holder can be moved from the microscope stage and transferred into separately pumped preparation and introduction chambers. *In-situ* sample heating (to 2000K and, potentially, cooling) is greatly facilitated by the grounded sample design mentioned above. Also, multiple ports are available for directing various evaporants toward the sample during microscopy. *Ex-situ* facilities exist for heat- and sputter cleaning of sample surfaces, for Auger analysis, and for well defined multiple layer vapor depositions.

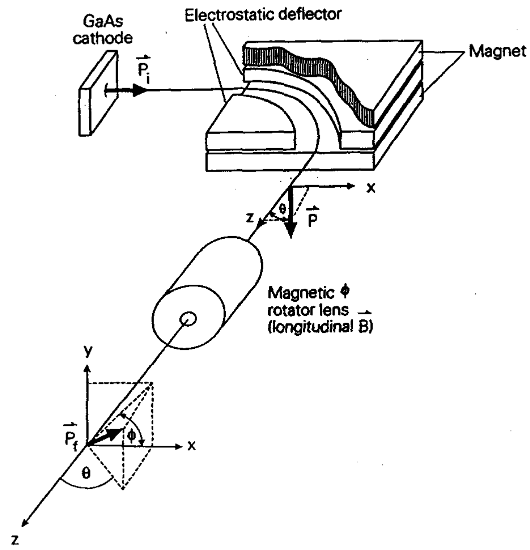

Fig. 2. Schematic arrangement of electrostatic and magnetic deflectors used to bend the laser excited electron beam onto the microscope axis and to influence the direction of the polarization vector P with respect to the x-y sample plane.

RESULTS

First results of *in-situ* epitaxial Co deposits on W(110) are summarized in Figs. 3 and 4 with the purpose of demonstrating the functioning of the principal modes of operation of this new microscope design. The lateral resolution obtained to date is of the order of 20 nm.

Figs.3a - 3d show a series of difference images with magnetic contrast distinguishing two in-plane domains separated by a jagged domain boundary. (The field of view in all figures is approximately 12 microns.) These difference images were obtained by digitally subtracting two images acquired with opposite spin directions and followed by some contrast enhancement, with the automated switching between the two polarization directions being accomplished with a liquid crystal variable retarder in the laser beam path. After in-situ sample cleaning, the 6 monolayer (ML) Co film was prepared by growing Co at substrate temperatures decreasing from about 400K to close to room temperature. The in-plane polarization direction of the illuminating electron beam was varied as indicated by the ϕ values in in Figs. 3a-3d for θ= const = 90°. As expected, magnetic contrast changes and reversals can be seen depending on the angle of the local sample magnetization with the polarization direction.

All images of Fig.3 were obtained near an image contrast maximum at 6.2 eV nominal energy of the impinging electrons (not taking into account the work function difference between cathode and sample).

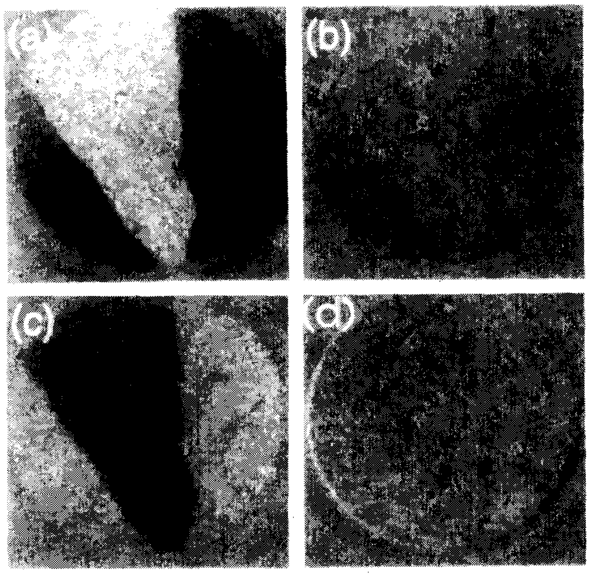

Fig 3. Demonstrating the effect of in-plane polarization direction (θ=90°) on magnetic domain contrast for 6 ML of Co on W(110). The magnetic image contrast changes from a positive maximum (a) for parallel alignment of polarization and sample magnetization (ϕ=150°, nominal) to near zero when ϕ increases by approximately 90° (b). A further increase by 90° leads to the negative maximum of contrast at antiparallel alignment (c). Yet another increase by 90° results in near zero contrast again (d).

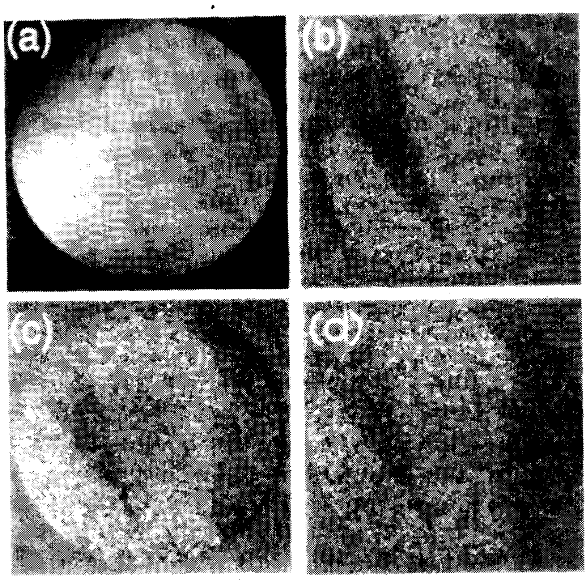

Fig 4. LEEM and SPLEEM images of 3 ML Co on W(110) still showing full in- plane magnetization. (a) is a single spin topographical (LEEM) image of the same sample area depicted in (b)-(d) as difference images. (b)-(d) show the effect of tilting the polarization out of the sample plane by 00 (θ=90°) (b), 30° (c), and 60° (d).

When changing θ at fixed ϕ from 90° (in-plane) to zero degrees, a cosinusoidal decrease of magnetic contrast can be detected indicating full in-plane magnetization of these domains.

The energy maximum shifts to to 4.3 eV for a thinner Co film on W(110) of about 3 ML thickness (Fig.4) which was prepared in a similar manner as the film of Fig 3. Since the difference images obscure, of course, all morphological surface structure detail, Fig.4a first shows a single-spin image emphasizing the surface features that survive the 3 ML Co deposition. Figs. 4b - d depict difference images of a different domain configuration as a function of θ for a ϕ = const = 150°. It is obvious that even for this thinner deposit, which results in a considerably noisier SPLEEM signal, the sample magnetization is found fully in-plane. In contrast to this result, a considerable contribution of out-of-plane magnetization was found for Co/Au(111) by SEMPA [10].

Conclusion

The design concept and operation of an advanced SPLEEM instrument have been discussed. This new design is characterized by three main features: a) Compactness of construction, b) multi-directional spin electron gun, and c) integration with a versatile sample preparation and exchange system. We have demonstrated the functioning of the principal modes of operation of this microscope which presently shows lateral image resolutions of the order of 20 nm. Magnetic domains in Co films of 3 and 6 ML thickness grown *in-situ* from the vapor phase have been used as test objects. They are fully in-plane magnetized with no out-of-plane components of magnetization detectable.

Acknowledgment

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