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Design and commissioning of an aberration-corrected ultrafast spin-polarized low energy electron microscope with multiple electron sources

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ABSTRACT

We describe the design and commissioning of a novel aberration-corrected low energy electron microscope (AC-LEEM). A third magnetic prism array (MPA) is added to the standard AC-LEEM with two prism arrays, allowing the incorporation of an ultrafast spin-polarized electron source alongside the standard cold field emission electron source, without degrading spatial resolution. The high degree of symmetries of the AC-LEEM are utilized while we design the electron optics of the ultrafast spin-polarized electron source, so as to minimize the deleterious effect of time broadening, while maintaining full control of electron spin. A spatial resolution of 2 nm and temporal resolution of 10 ps (ps) are expected in the future time resolved aberration-corrected spin-polarized LEEM (TR-AC-SPLEEM). The commissioning of the three-prism AC-LEEM has been successfully finished with the cold field emission source, with a spatial resolution below 2 nm.

1. Introduction

Low energy electron microscopy (LEEM) and photoemission electron microscopy (PEEM) using low energy electrons (0–100 eV) are powerful tools in surface and interface science [1–4] to investigate surface dynamics in real time and real space [5–9]. Recently, tremendous progress has been made in aberration corrected (AC) LEEM, with a spatial resolution of 1.4 nm, approaching the ultimate predicted spatial resolution of 0.6 nm [10,11]. The development of AC-LEEM, including a comprehensive wave-optical imaging theory and highly modular components in the instrument design, make it possible to add new functions to expand its range of applications, while maintaining the accessibility and reliability of the instrument.

However, all LEEM instruments available today are working with continuous electron sources. The integration of an ultrafast electron source into LEEM would enable us to study various dynamical processes on bulk samples with dramatically improved temporal resolution in current instrumentation such as surface phase transitions, photo-chemical reactions, melting-crystallization processes, self-assembly, charge harvesting in solar cells, and switching in phase change memory. For example, martensitic phase-transformation of iron has been demonstrated by ultrafast TEM [12], ultrafast LEEM/LEED could be very critical to reveal details of surface process in particular heated-assisted phase transition for nano-scale structures on the surface including ferromagnetic phase transition. For photochemistry using UV to infrared pumps, ultrafast mode is sensitive to surface reaction under excitation. These will open up new opportunities for studying surface dynamic processes with LEEM. Furthermore, if the electron spin is well-controlled, ultrafast spin dynamics of magnetic domains can be investigated at high spatial and temporal resolution. This capability is highly desirable to further our understanding in nanoscale magnetic properties and processes, which dominate the performance of devices ranging from high density magnetic data storage to magnetic sensor and spintronics devices. In combination with ultrafast spin polarized low energy electron diffraction and imaging, the system will enable us to understand the correlation between structure and magnetism in ultrafast processes on surfaces at the nanoscale.

In contrast to transmission electron microscopy (TEM) equipped with ultrafast electron guns [13–18], the electron optics of the ultrafast

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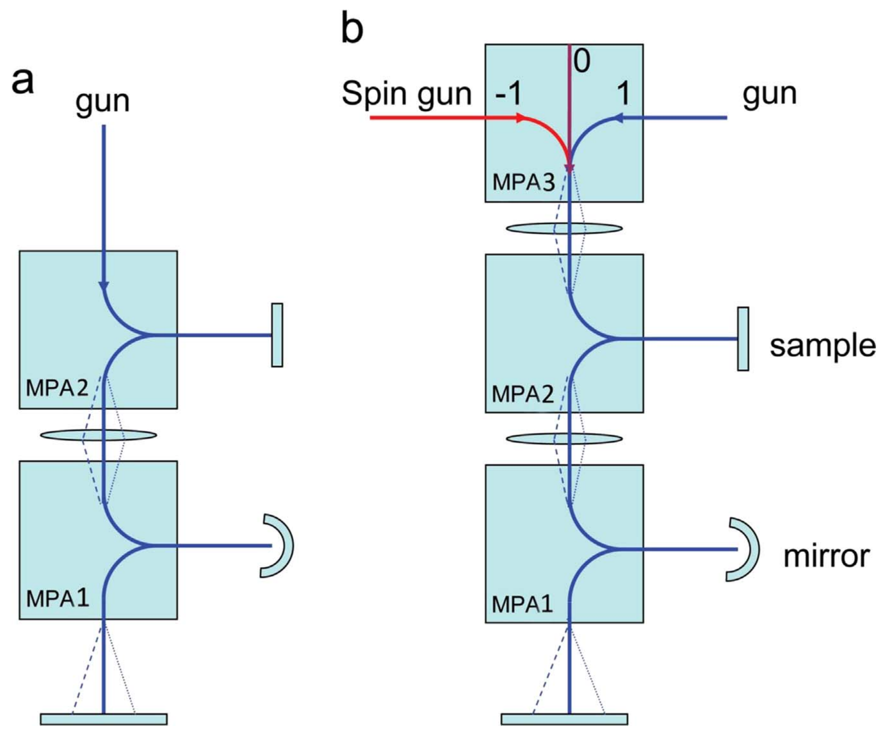

Fig. 1. Schematic diagrams of standard two-MPA and three-MPA designs for aberration-corrected and energy-filtered LEEM systems. (a) Standard design with two dispersive prism arrays. Between the two MPAs, electrons with different energies are dispersed (dashed and dotted lines). (b) The new design with three identical dispersive MPAs. The FEG electron beam (blue) dispersion is removed in front of the sample and mirror due to the symmetry of MPAs. The dispersion of the ultrafast spin polarized electron beam (red) can't be removed by symmetry alone. It can be compensated by combination of a 90° spin deflector and electrostatic quadrupoles (EQ) to achieve high temporal resolution of 10 ps (see Section 3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

spin-polarized (SP) electron gun requires extra sophisticated electron optics to control the electron spin and minimize aberrations. In this paper, we present the design and commissioning of a new AC-LEEM instrument capable of integrating multiple electron sources: an ultrafast spin-polarized electron gun and a standard cold field emission gun (FEG).

In Section 2, we will present the physical design of a novel triple magnetic prism array (MPA) AC-LEEM compatible with multiple electron sources. Section 3 explains the electron-optical design of the ultrafast aberration-corrected spin-polarized (SP) electron gun. A simulation of the TR-AC-SPLEEM performance is presented in Section 4. The successful commissioning of the 3-MPA AC-LEEM is reported in Section 5. We finish with summaries and outlooks.

2. Design of an AC-LEEM with multiple electron sources

Fig. 1a shows the system layout of the standard AC-LEEM instrument with only a cold field emission electron source. The electron beam, originating from the gun mounted on top of MPA2, is deflected over a 90° angle to the objective lens optics and sample to the right of MPA2. After reflecting from the sample, the beam returns to MPA2 where it is deflected again counterclockwise by 90 degrees. A diffraction pattern is located at the entrance plane of MPA2, and a real image is at the center of MPA2. MPA2 transfers the diffraction pattern to its exit plane, centered between MPA2 and MPA1, in the center of an electrostatic transfer lens. This lens transfers the real image from the center of MPA2 to the center of MPA1. MPA1 deflects the beam in the aberration correction column containing a four-element electron mirror and associated transfer optics [19] to compensate the spherical and chromatic aberration coefficients of the objective lens. After return from the mirror, MPA1 deflects the electron beam one more time into the projector column. The projector lenses can be set to display either the real-space image or the diffraction plane onto the image detector. As described in detail in ref. [4], this compact and modular optical system takes optimal advantage of various mirror symmetries (around the MPA diagonals as well as around the mid-plane between the MPA's) to minimize or even eliminate numerous undesirable aberration terms.

However, this geometry does not lend itself to adding additional electron sources to the system. A third MPA, as shown in Fig. 1b, provides ample flexibility to add two additional electron guns as shown. Adding a third MPA is straightforward, as it reutilizes electron-optical design elements and components already present in Fig. 1a. Thus, we may install electron sources in positions 1 (90 degrees counterclockwise deflection), 0 (no deflection) and −1 (90 degrees clockwise deflection). In each case the beam exits at the bottom of MPA3, and is transferred into MPA2 in the usual manner. The lower microscope system is identical to Fig. 1a, and utilizes all the same symmetries. We moved the cold FEG from its usual location in Fig. 1a, to position 1 (90° counterclockwise deflection) in Fig. 1b. This layout has the advantage of forming an achromat between the electron gun and the sample. Chromatic dispersion of the electrons by deflection in MPA3 is canceled due to the symmetry by subsequent deflection in MPA2. Thus, the electron beam is dispersion-free in the objective lens column. This is not the case in Fig. 1a, although the small chromatic dispersion due to the energy spread of the cold FE gun (< 0.25 eV) does not marginally degrade the performance of the microscope in that case.

The detailed electron-optics of our three-MPA AC-LEEM is schematically presented in the Phase-I of Fig. 2. It is an improved version of the SPECS FE-LEEM P90 AC according to the design of Ruud Tromp [4,19,20]. In order to implement an extra ultrafast electron gun, a third magnetic prism array (MPA3) is added to the top of the FE-LEEM P90 AC with MPA2 and MPA1. The new MPA3 couples to MPA2 via an additional electrostatic transfer lens, which transfers the image from the image plane of MPA3 to the image plane of MPA2. The whole project of time resolved AC-SPLEEM system will be accomplished in three phases. Phase I is the construction of an AC-LEEM with three magnetic prism arrays (MPAs), which has been successfully commis-