Development of Spin-Polarized Pulsed TEM

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Abstract. Recent nanointegration of magnetic storage and spintronic devices is expected to lead to the development of systems that can analyze magnetic and spin states with a nanometer-order spatial resolution. Development of a polarized transmission electron microscope (SPTEM) that employs a spin-polarized electron source (PES) has commenced at Nagoya University. A spin-polarized electron beam is extracted from a photocathode that has a negative electron affinity surface. The temporal profile of the electron beam can be modulated by varying the temporal profile of the driving laser. The SPTEM can obtain temporal and spatial information about spin. The design and construction of the PES were optimized for the SPTEM. A beam energy of less than 40 keV (a low energy for a TEM) was used because the spin interaction with condensed matter is very small compared with the Coulomb interaction. A polarized electron gun was realized in an extreme high vacuum by applying a high field gradient of 4 MV/m to the photocathode surface. A 40-keV polarized electron beam with sub-millisecond pulses was generated using a backside-excited photocathode. The illumination system of the TEM was designed with the aim of producing a spin-polarized electron beam. The system contains two components that rotate spin: one performs azimuthal rotation and the other performs in-plane rotation in the condenser magnet system. The SPTEM has the potential to dynamically generate magnetic-field images with high contrast and high temporal resolution.

1. Introduction

Great advances have been made in magnetic recording technology and spintronic devices, which are promising for high-density storage devices [1–3]. Such devices are expected to lead to the development of systems that can analyze magnetic and spin states with a nanometer-order spatial resolution. Already an electron beam holography and a Lorentz electron microscopy have been used for observation of magnetization state of magnetic recording media as well as spin-detection scanning electron microscopy where image resolution is, however, restricted to larger than 5 nm [4]. A spin-resolved STM (SP-STM) realizes the performance in atomic scale [5]. Although the SP-STM can only observe the surface state of spin, and the measurable direction of magnetization is limited due to the probe tip. It is important that the inner spin-state can be observed directly in arbitrary direction with atomic scale.
Development of polarized electron sources (PES) has been advancing in the field of high-energy physics [6,7]. PES technology has been intensively developed from the mid-1980s to enable experiments using polarized electron beams to be performed at the International Linear Collider (ILC) [8]. PES technology has recently been applied to materials science instruments to observe surface magnetic phenomena [9,10]. Electron spin is very important for both fundamental physics and some key technologies such as spintronics and quantum-information technology [2,3].

We have been seeking to combine electron microscopy and accelerator technology to produce a spin-polarized transmission electron microscope (SPTEM), which consists of a PES and a conventional TEM. We have commenced developing a PES for a TEM [11]. Spin-polarized electrons can be generated using an optical orientation of appropriate III–V semiconductors and vacuum extraction that uses a negative electron affinity (NEA) surface. Circularly polarized laser light illuminates a semiconductor and spin-selectively excites valence electrons into the conduction band. These polarized conduction electrons diffuse and some of them drift to the surface region. They are then extracted through the NEA surface in a vacuum by applying a negative electrostatic field. Several beam parameters (including the electron spin polarization (ESP), the quantum efficiency (QE), and the beam emittance) of the PES are vastly superior to those of conventional electron beams. In addition, it has the ability to generate a sub-nanosecond multibunch beam. A high ESP of 92% and a high QE of 0.5% have been realized using a GaAs–GaAsP strained superlattice photocathode with a 100-nm-thick active layer that was excited with 780 nm wavelength light [12,13]. A normalized thermal beam emittance as low as 0.15π mm mrad can be achieved. This high-performance PES will enable dynamic observation of magnetic structures with high spatial and temporal resolutions in TEM. We have commenced developing a SPTEM. This paper presents an overview of the SPTEM and related systems.

2. Spin-polarized TEM system

Figures 1 and 2 respectively show photographs and a schematic diagram of the SPTEM system. The SPTEM consists of a PES, an illumination-lens system that includes a spin manipulator, an objective-lens system, a projector-lens system, and an image-detection system. The PES has been designed and constructed with optimization for SPTEM [11]. The beam energy is set to be below 40 keV, that is a lower energy type as a TEM, because the spin interaction with condensed matters is very small comparing with the Coulomb interaction [14]. The polarized electron beam emitted from the PES passes through a spin rotator and the condenser-lens (CL) system focuses the polarized electron beam onto the specimen. As the beam passes through the specimen, some electrons are scattered by...
interactions such as the Coulomb interaction, the spin–orbit interaction, and the spin–spin interaction. The modified beam then passes through the objective and projector lenses that focus it onto a fluorescent screen or the imaging plate of a CCD camera to obtain the final image. Since the electron beam passes through the specimen, the diffraction pattern obtained gives comprehensive information about the interior of the specimen, including its magnetic distribution. Except for the detection chamber, an ultrahigh vacuum (UHV) is maintained throughout the vacuum system in the SPTEM to prevent residual gas from destroying the NEA surface. The illumination-lens system was developed in this study. It consists of a spin rotator for polar rotation (SRB) and a CL system that contains in-plane spin-rotation magnetic lens (SRL). A 90° bending system was employed for the SRB; it generates both electric and magnetic fields to rotate spin by an arbitrary angle. The system can also correct for over-rotation due to relativistic effects such as the anomalous electron magnetic moment and Thomas precession [15]. This is important since if the spin rotator only used an electric field to bend the trajectory of a 40-keV beam by 90°, the actual spin-rotation angle relative to the beam axis will be 96.6° according to the Thomas–BMT (Bargmann-Michel-Telegdi) equation [15].

![Figure 2. Schematic of SPTEM and components](image)

3. Spin rotation system in illumination optics of TEM

Spin rotators are necessary to control the spin direction of the polarized electron beam. Electrons emitted from the photocathode have spins that either parallel or antiparallel to the beam axis due to the quantization axis of the semiconductor photocathode and the helicity of the excitation light. This system requires two spin rotators to rotate both the polar and azimuth angles.

A 90° bending system was employed as a spin rotator for the polar angle because the PES is installed on top of a TEM. In the SRB, spin precession due to an electric field rotates the spin vector relative to the injected beam axis, but bending of the beam trajectory by 90° is achieved by applying a magnetic field whose magnitude balances the Lorentz force [15]. The polar angle between the beam direction and the spin direction can be controlled to any value. The spin rotation system was carefully designed to maintain both the UHV and a high brightness. An electric field is generated by a spherical condenser with a radius of curvature of 100 mm. A transverse magnetic field is generated by a pair of magnetic poles that are separated by 30 mm. To prevent degradation of the UHV, the magnet coils that
generate the magnetic field are located outside the vacuum chamber and the magnetic field is guided through the magnetic poles into the vacuum. On the other hand, the spin can be rotated azimuthally in the transverse plane by the magnetic field generated by the SRL magnet in the series of CL magnets. The CL system essentially collimates and concentrates the beam onto the specimen. In the present system, the CL system also acts as a spin rotator for in-plane rotation. The system consists of four magnetic lens: SCL1, SRL, SCL2, and SCL3. In the beam optics, the electron beam from the 90°-bending spin rotator is focused onto the center of the SRL by SCL1 since the beam trajectory will not be altered in SCL2 regardless of the magnetic field strength in the SRL. SCL2 and SCL3 play function as a CL in a TEM. This CL system can thus realize in-plane spin rotation and concentrate the beam onto the specimen.

4. Summary

We have constructed all the components of a SPTEM, namely a polarized electron source, spin rotators, double-gap CL magnets, an electron energy loss spectrometer, and a TEM. The PES can generate a high performance electron beam for the SPTEM. The spin rotation system can be used to completely control the spin of the electron beam since it accounts for relativistic effects. This SPTEM can rapidly image magnetic structures using spin-dependent contrast.

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