Development of Fourier transform holography imaging using soft and hard X-rays

With the recent development of coherent X-ray sources including free electron lasers or high-harmonic tabletop lasers in addition to state-of-the-art synchrotron radiation, interest in coherent imaging of nanomaterials has been growing. Among these imaging techniques, X-ray Fourier transform holography (XFTH) provides unambiguous image recovery by direct Fourier inversion. A first hologram in the X-ray region was reported in 1974 by Aoki *et al*. [1]. In 2004, Eisebitt *et al*. demonstrated the magnetic worm domain imaging of a Pt/Co perpendicular magnetized film by applying an integrated holography mask and sample design at soft X-ray [2]. In the lensless Fourier transform holography, as shown in Fig. 1(a), an observed scattering intensity can be written as $I=|A+R|^2=|A|^2+|R|^2+AR^*+A^*R$, where A is the scattering amplitude from the image and R is the reference amplitude from the point source. From the interference term $AR^*(=H)$ and $A^*R(=H^*)$, the sample image can simply be recovered by a Fourier inversion of H. We tried to extend the technique to be suitable for observing nanomaterials under various conditions by using soft and hard X-rays [3].

To perform an *in situ* observation of magnetic domain at high temperature, we developed an XFTH equipment as shown in Fig. 1(b) at the soft X-ray beamline **BL25SU**. A pinhole was placed to collimate the incident X-ray beam. A charge-coupled device (CCD) was used to record the hologram. To fabricate the integrated mask sample of Pt/Co, a 1.7-μm-thick Au layer was deposited on a SiN membrane. An illumination window of 2 μm square shape and a 0.1-μm-diameter reference hole were formed by focused ion beam (FIB). The Pt/Co layer was formed on the backside of the membrane. By applying a circularly polarized X-ray at the energy of Co L_3 edge (778 eV), we succeeded in observing the change in the magnetic domain as shown in Fig. 2(a). The results demonstrate that the method can be applied to such a high temperature. While the technique has been successfully applied, a weak point of this method is a narrow field of view of approximately 2 μm size, which was determined on the basis of the transverse coherent length and the off-axis configuration to avoid image overlapping. Another weak point is the difficulty in fabricating the integrated mask-sample specimen.

To solve the problem, we developed a scanning-type XFTH where the holography mask and imaging object was separately prepared and moved in contact with each other as shown in Fig. 1(c) and 1(d). With this configuration, we can scan the sample using a high-precision stage, and the holography mask can be used for other measurements. To confirm the method, the experiments were performed at beamline BL25SU using soft X-ray, and beamline **BL16XU** (Sunbeam) using hard X-ray. A sample can be moved by a piezo-driven X–Y translation stage. The sample stage was placed in the vacuum chamber. Figure 2(b) shows the extended magnetic domain image obtained by combining the seven images measured at each position. The spatial resolution estimated from the edge impact was 42 nm. Recently, similar results

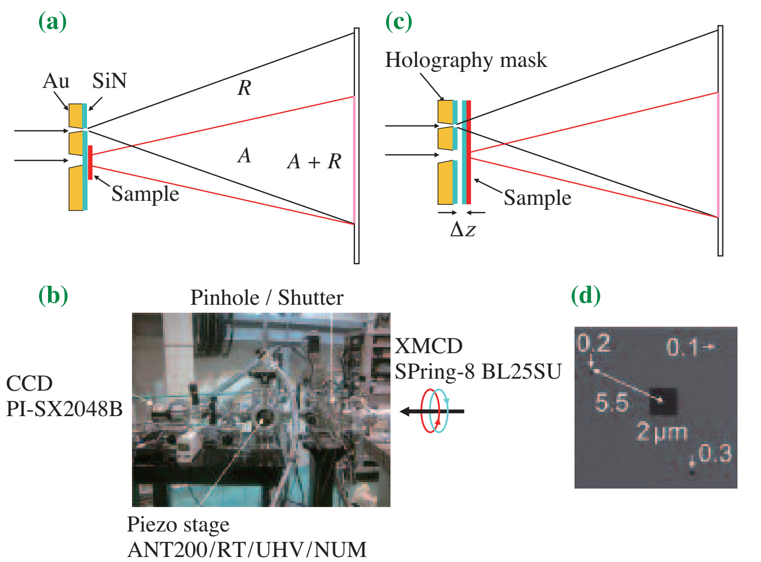

Fig. 1. **(a)** Schematic of XFTH using integrated mask-sample design. **(b)** Experimental setup of soft X-ray FTH at BL25SU. **(c)** Schematic of mask and sample separated by XFTH. **(d)** An example of holography mask.

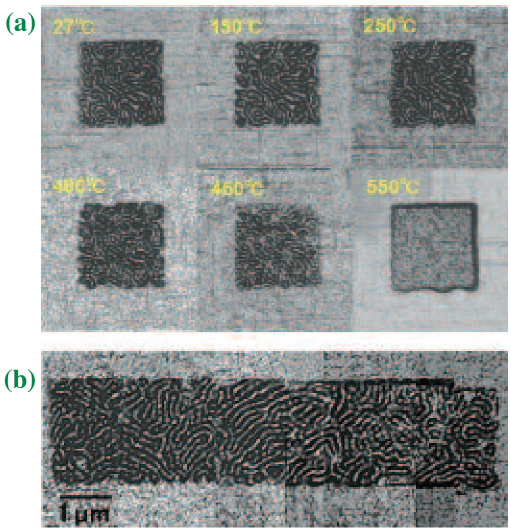

Fig. 2. **(a)** Magnetic domain pattern observed at several temperatures. The pattern changed above 400°C. **(b)** Magnetic domain in the 8 μm area, which was obtained by connecting seven recovered images measured at each position.

obtained using a circular-shaped window have been reported [4], which indicates that the method can be applicable to window of various shapes.

A hard X-ray has a high penetration power and the measurement can be performed in air ambient. XFTH experiments in the hard X-ray region have been performed at beamline BL16XU at an X-ray energy of 5500 eV. To prepare the hard X-ray holography mask, a 3.4 μm Au layer was deposited on a SiN membrane. The illumination window of 2 μm square shape and a 0.2-μm-diameter reference hole were fabricated by FIB. As a first sample, an artificial pattern of "XFEL" was milled in a Au film as shown in the upper part of Fig. 3(a). For the second sample, a cross-sectional sample of a Cu interconnect line with line and space of 0.27 μm was prepared. A detailed structure of the Cu line is shown in the upper part of Fig. 3(b). The thickness of the sample was 2 μm.

The lower part of Fig. 3(a) shows the extended image of an artificially patterned sample by combining 5 recovered images. The lower part of Fig. 3(b) shows the cross-sectional images of the Cu line. The estimated spatial resolution was 75 nm. A reason for the low resolution compared to the case of soft X-ray is the blurring due to the reference hole size of 0.2 μm, since the obtained image is a convolution of the original image and the reference hole image.

To avoid the resolution reduction in this method, we developed a deconvolution technique in which the measured hologram was divided by the estimated reference amplitude as H'=H/R*. Here, H' denotes the hologram after blurring correction. Figure 3(c) compares the original image (left) with that after the correction (right). The spatial resolution has been improved from 75 to 50 nm.

In conclusion, we applied the XFTH imaging technique for the *in situ* observation of magnetic domain pattern at high temperature. We developed a technique to extend the field of view by applying the separated mask and sample design. In addition, the problem of image blurring owing to a finite size of reference source was corrected by dividing the hologram by the estimated reference amplitude. After the treatment, the spatial resolution for hard X-ray improved from 75 to 50 nm.

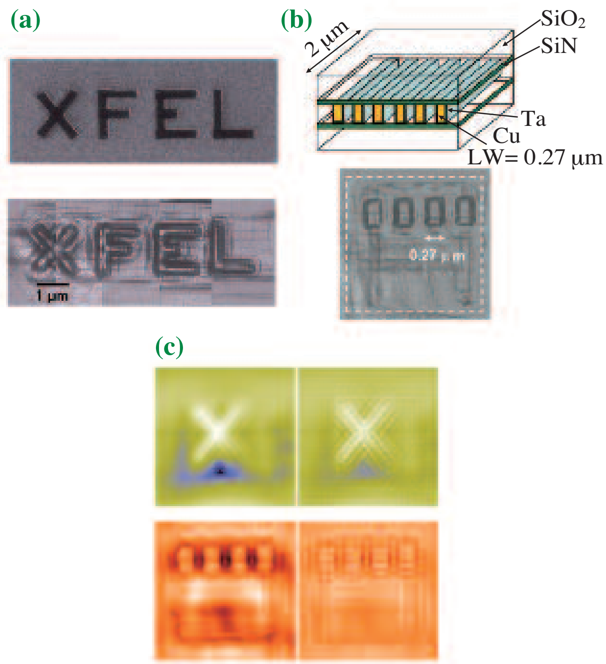

Fig. 3. **(a)** Upper is the SEM image of an artificial pattern with a width of 7 μm. Lower is a recovered image obtained by connecting five images measured at each position. **(b)** Upper is the structure of the Cu-interconnect-line sample. Lower is the recovered cross-sectional image. **(c)** Original image (left) and corrected image (right) of the artificial pattern (upper) and Cu-line sample (lower).

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