Time-resolved imaging of an operating hard-disk-drive write head using nanobeam X-ray magnetic circular dichroism

Hard disk drives (HDDs) are the principal storage device for digital technology, and thus, there is strong demand to increase the capacity to keep pace with the continuing growth of digital data. In a write operation of HDDs, a write head generates a localized magnetic field (recording field) on a magnetic recording medium and changes the magnetization direction. To generate a recording field in a small area, state-of-the-art HDDs have a main pole with a tip of sub-100-nm dimensions, and magnetization patterns written on the medium have a lateral size of ten to a few tens of nanometers, leading to an areal density exceeding 1 Tbit/inch^2. The write operation is completed in less than 1 ns. For the development of higher-capacity HDDs, elucidating the magnetization dynamics of the write head is of technological importance. However, experimental measurement has been difficult because of the small dimensions and high operation speed. In this research, we used the time-resolved nanobeam X-ray magnetic circular dichroism (XMCD) microscope installed at the soft X-ray beamline, SPring-8 **BL25SU** [1,2] and studied the dynamic behavior of an HDD write head under the operating condition [3]. XMCD has distinctive capacities such as nanometer-scale spatial resolution and sub-nanosecond time resolution. Because these resolutions are compatible with the dimensions and operation speed of the HDD write head, XMCD is suitable for studying its dynamic behavior.

Figure 1(a) shows a schematic image of the sample. The HDD write head used in this study was developed for perpendicular recording and is capable of recording at a density of 200 Gbit/inch^2 and writing at a speed of 700 Mbit/s. The HDD write head consists of a main pole, a shield, and a coil. The main pole and shield are composed of a magnetic material, and the tip of the main pole and part of the shield are exposed on the air-bearing surface (ABS). By introducing a write current to the coil, the magnetization of the main pole and shield is changed, generating a recording field localized around the main pole tip. In actual HDD operation, the ABS faces a recording medium with a very small flying height of approximately less than a few nanometers between them. As the recording medium moves in the direction depicted as the down-track direction, the recording field changes the medium magnetization, leaving recorded patterns. Figure 1(b) shows a scanning electron microscopy image of the ABS of the write head. Namely, the write head is seen from below in Fig. 1(a). The size of the main pole tip is approximately 250 nm × 120 nm. Figure 1(c) shows the measurement setup. In A-mode operation, electron bunches circled the storage ring at intervals of 23.6 ns. Right or left circularly polarized soft X-ray pulse beams were selectively generated by twin helical undulators, focused down to approximately 100 nm by an order-sorting aperture (OSA) and a Fresnel zone plate (FZP), and scanned over the ABS of the write head. The incident angle was normal to the ABS. For detecting X-ray absorption, electrons emitted by X-ray absorption were collected by the voltage-biased OSA. Time-resolved measurements were realized by the synchronized timing control in which the write head was reversed at intervals of 2.36 ns (one-tenth of the cycle of the periodic X-ray pulses) by using an RF square-wave write current. The delay of the RF write current with respect to the X-ray pulses was varied to obtain snapshot magnetization images. XMCD images were generated by measuring two X-ray absorption (XA) images at right- and left-hand circular polarizations and calculating the subtraction of the signals from the two images normalized by their summation. The resulting XMCD signal represents the z-component magnetization of a selected element.

Figure 2 (a) shows the XA image obtained with the X-ray energy at the Fe L_3 absorption edge.

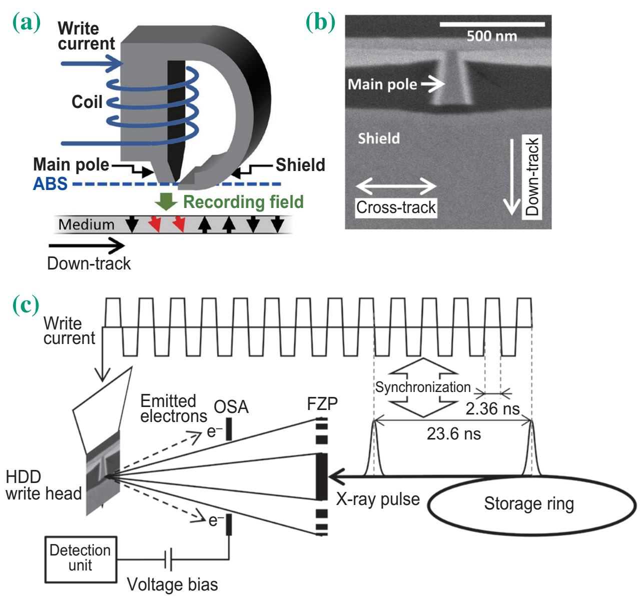

Fig. 1. **(a)** Schematic image of the HDD write head and its operation. The arrow of the down-track direction indicates the flying direction of the recording medium. **(b)** SEM image of the ABS of the write head. **(c)** XMCD measurement setup using the OSA collection method and timing control for time-resolved measurement.

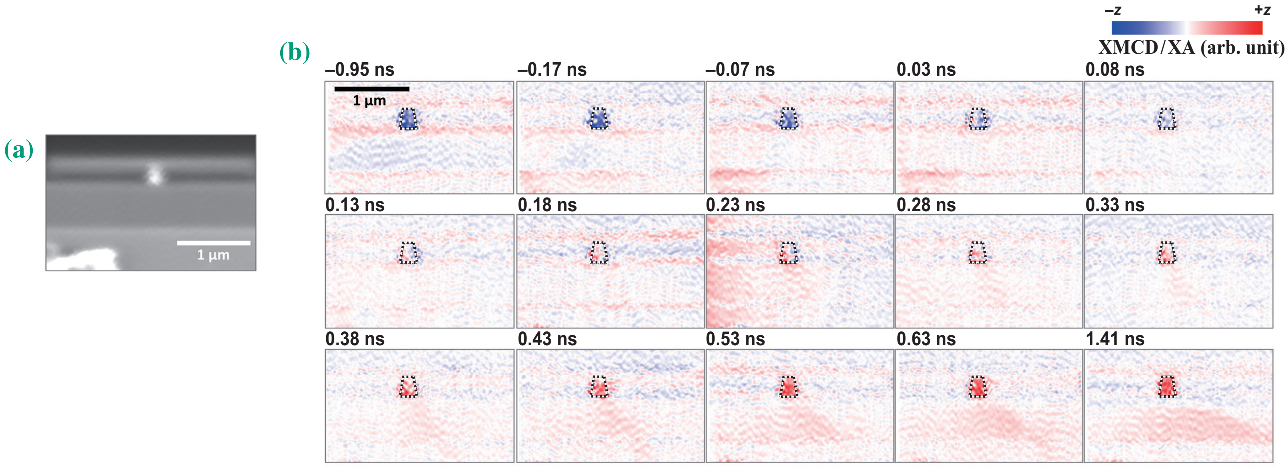

Fig. 2. **(a)** X-ray absorption image of the ABS of the write head obtained at the Fe L_3 absorption edge. **(b)**Time evolution of snapshot XMCD images. Dotted trapezoids show the positions of the main pole estimated from the XA image.

This image was taken at the same position as the SEM image in Fig. 1(b). The main pole exhibits a large signal because it is composed mainly of Fe. Figure 2(b) shows the time evolution of snapshot XMCD images obtained by changing the delay. Note that the time intervals between the images are not uniform and is as small as 50 ps around the transition. The dotted trapezoids show the position of the main pole estimated from the XA image. With time, the magnetization of the main pole decreases, and a demagnetized state appears. Then, the magnetization increases to the opposite polarity and the magnetization reversal is complete. The time interval between the first and last images is 2.36 ns, indicating that they were obtained at opposite phases of the RF write current. Figure 3(a) shows a waveform of the RF write current and Fig. 3(b) shows the intensity of the XMCD signal averaged over the main pole area as a function of time. The magnetization reversal of the main pole occurs from –0.17ns to 0.53ns, and the slope over time is nearly linear. The slope is more gradual than that of the write current, indicating that the main pole reversal is determined mostly by the response of the write head. These results show that the XMCD measurement setup developed in this study is a powerful tool for understanding the dynamic behavior of an HDD write head and contributes to the development of higher-capacity HDDs.

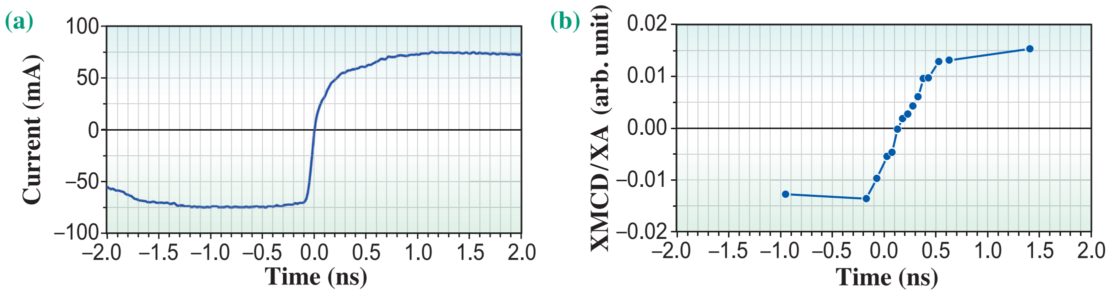

Fig. 3. **(a)** Waveform of the RF write current. **(b)** Average XMCD signal of the main pole area versus time, calculated from the data in Fig. 2(b). Note that the time axes in (a) and (b) are irrelevant because the absolute delay between the RF write current and the X-ray pulses is unknown.

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