Z_{eff} Imaging Using X-Ray Interferometer

Z_{eff} imaging is a new technique that provides a way to visualize the spatial distribution of the atomic number (Z) in samples (effective atomic number (Z_{eff}) for a plural-element sample). Because Z corresponds to the ratio of the real to imaginary part of the complex refractive index, an elemental map can be calculated from an absorption and phase-contrast image. Feasibility observations of several metal foils were performed using an imaging system fitted with a two-crystal X-ray interferometer. The obtained Z_{eff} image shows that aluminum, iron, nickel, and copper foils were clearly distinguished, and that the Z_{eff} values for nickel and copper coincided with the ideal Z number within 5%.

X-ray imaging is a powerful method for nondestructive observation of samples and is widely used in many fields from medical diagnosis to security checks at airports. Obtained images show the electron density distributions in a sample, and the outer shapes and inner structures are visualized clearly. However, no elemental information of the sample, for example, whether the sample consists of copper or iron, is obtained. An X-ray is an electromagnetic wave with a very short wavelength. The phase is shifted and the amplitude (intensity) is reduced by passing the X-ray through the sample. The phase-shift dp is given by the product of the thickness of the sample (t) and the real part of the complex refractive index (n) of the sample. In the same way, the ratio of the decrease of the intensity dI is given by the product of t and the linear absorption coefficient corresponding to the imaginary part of n. Therefore, the ratio (r) of dp and dI is independent of t, and only depends on the ratio of the real and imaginary parts of n. Since n has a characteristic value for each element, ratio r also has a characteristic value. In summary, ratio r uniquely corresponds to the element, namely the Z-number of the sample, and therefore, elemental information can be obtained from r [1, 2].

An X-ray interferometer is a powerful tool to detect X-ray phase shift, and has been used for phase-contrast X-ray imaging with more than 1000 times higher sensitivity than that of conventional absorption X-ray imaging [3]. Because of this advantage, it provides a way to visualize small density differences in samples composed of light elements, for example, biological soft tissues and organic materials without using any supplemental methods. We have been developing an imaging system fitted with a two-crystal X-ray interferometer to conduct fine three-dimensional (3D) observations [4]. We used this system to conduct visualizations of cancerous tissues in normal tissues without contrast agents, β-amyloid plaques in brains taken from Alzheimer's disease mice [5], and air hydrates in an ice core drilled 1900 m deep in the Antarctic [6]. By exploiting the high sensitivity of phase-shift detection, highly accurate observations of the Z_{eff} image using the X-ray interferometer were performed [7].

Figure 1 schematically shows the two-crystal X-ray interferometer used in our study. The optical configuration is the same as that of a Mach-Zehnder interferometer of visible light. The incident X-ray is divided at the first wafer (S), reflected by the second (M1) and third (M2) wafers, and recombined to generate two interference beams at the fourth wafer (A). The phase-shift caused by the sample put in the interference path (P1) can be detected by the changes in the interference beam intensity. Absorption images can be obtained by blocking off the beam path (P2) by placing a plate made of a heavy metal such as Pb.

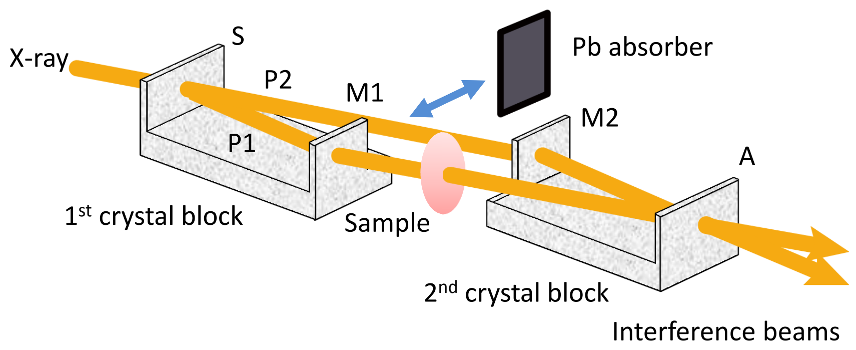

Figure 1: Schematic view of two-crystal X-ray interferometer.

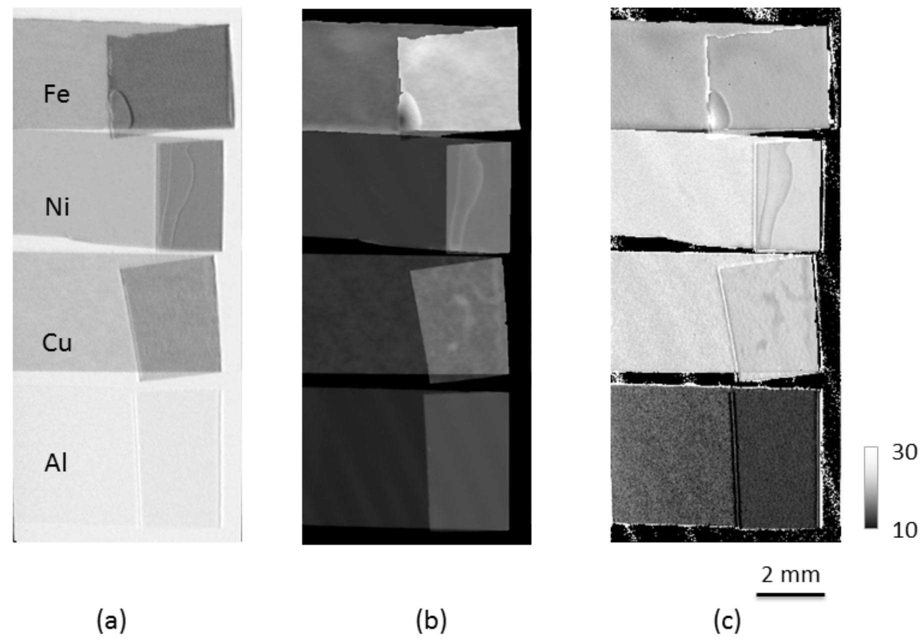

Figure 2: Obtained images of metal foils: (a) absorption image, (b) phase-contrast image, and (c) Z_{eff} image [8].

Figure 2 shows the obtained phase map (spatial distribution of phase-shift of sample), absorption map, and calculated Z_{eff} image. The metal foils were aligned vertically in the following order: iron (10 µm), nickel (5 µm), copper (5 µm), and aluminum (12 µm). Each foil is depicted clearly in ordinary images ((a) and (b)), but it is impossible to distinguish differences in the elements and their thicknesses. In contrast, the Z_{eff} image shows the Z_{eff} value of the samples and indicates that the elements are different. The average Z_{eff} values were 16.4, 25.4, 27.9, and 28.8 for aluminum, iron, nickel, and copper foil, respectively. The differences from the ideal values (13, 26, 28, 29) become smaller as the atomic numbers become larger, and the minimum value is less than 5%, which provides a way to identify the element. In addition, since the thickness information of the sample was canceled by the division of dp and dI, the Z_{eff} in each foil has the same value in the unfolded and folded areas (right side of the foils). This result shows that this imaging technique provides a way to obtain not only the electron density map but also elemental information without using any other imaging techniques. By combining this technique with computed tomography techniques, 3D elemental observations are expected in the future.

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