Development of Display-Type Ellipsoidal Mesh Analyzer

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We have been developing a new display-type ellipsoidal mesh analyzer (DELMA), which is composed of a wide acceptance angle electrostatic lens (WAAEL) unit and a transfer lens system. By using this analyzer, both photoelectron angular distribution patterns and magnified images of the sample can be obtained on a screen. When the screen is taken away from the electron path, the electrons are introduced to an energy analyzer (VG SCIENTA R4000) and high energy resolution spectra are obtained. A performance test of DELMA using synchrotron radiation was carried out at BL07LSU in SPring-8. We succeeded in measuring for the first time the magnified image of the sample, the angular distribution patterns, and x-ray photoelectron spectra. The magnified image from a mesh sample (SUS316, #100) was measured by using DELMA. The measured acceptance angle of angular distribution patterns using DELMA combined with the energy analyzer was about ±45°. We measured x-ray photoelectron spectra from a Ta plate to evaluate the energy resolution of DELMA. The measured total energy resolution of DELMA combined with the energy analyzer was 0.2% at kinetic energy around 700 eV.

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I. INTRODUCTION

Our group has been developing a two-dimensional display-type spherical mirror analyzer (DIANA) for two-dimensional photoelectron intensity angular distribution (2D-PIAD) measurements at the circularly-polarized-light soft x-ray beamline BL25SU of SPring-8 [1–5]. The 2D-PIAD of polar angles from 0 to 90° and azimuthal angles from 0 to 360° can be measured within seconds or minutes using this analyzer.

Forward focusing peaks (FFPs) which indicate surrounding atom directions appear as bright spots in the 2D-PIAD at kinetic energies above several hundred eV. FFP rotational shift caused by circularly-polarized-light excitation provides information on an interatomic distance between the emitter and scatterer atoms [1]. The intensity modulation in the 2D-PIAD of core-level photoelectron contains not only FFP but also the interference between the direct wave and the scattered waves. The 2D-PIAD can be considered as an atomic stereo photograph [1] as well as a photoelectron hologram [6–8], which can visualize a three-dimensional local atomic arrangement around the emitter atom. This method is applicable to the analysis of the atomic structure of not only bulk crystals but also impurities or adsorbates, which have no translational symmetry in crystal. We succeeded in observing many patterns of photoelectrons, Auger electrons and valence band electrons [3–5]. However, DIANA gives an averaged diffraction pattern of the irradiated area and cannot distinguish individual small regions.

The recent development of the photoemission electron microscope (PEEM) [9] is remarkable. Recent PEEM has an energy analyzer and can carry out photoelectron spectroscopy on individual regions as small as 30 nm. The chemical composition and electronic states of individual small regions can be studied using PEEM. However, normally PEEM cannot measure photoelectron diffraction patterns because the acceptance angle of PEEM at the kinetic energy around 700 eV is about ±15°, which is not enough to detect photoelectron diffraction. We considered that the combination of photoelectron diffraction and spatial images acquisitions will have an impact on the field of surface science. Therefore, we have developed a new analyzer, the Display-type Ellipsoidal Mesh Analyzer (DELMA) [10–16].

DELMA can measure the 2D-PIAD at any kinetic energies, and has the advantages of being a display-type analyzer for measuring 2D-PIAD with the capabilities of photoemission electron microscope. The designed acceptance angle of DELMA is the polar angle from 0 to 45° and azimuthal angles from 0 to 360°. Figure 1 shows a schematic drawing of DELMA, composed of Wide Acceptance Angle Electrostatic Lens (WAAEL) unit, a transfer lens system and a screen. DELMA is combined with an energy analyzer (VG SCIENTA R4000).

The key component of DELMA is an ellipsoidal mesh for measuring the wide-angle 2D-PIAD [10–16]. The accuracy of the mesh shape and the size of the mesh holes determine the performance of WAAEL [15]. It is difficult to collect electrons in wide angles by conventional electron lens, because the spherical aberration of the electron lens increases rapidly when the acceptance angle increases. In
contrast, WAAEL enables correction of spherical aberration over a wide acceptance angle up to ±60° [10]. We can get the wide-angle 2D-PIAD using WAAEL. We succeeded in observing an image magnified 5 times from a mesh sample (SUS 316, #250) by using only WAAEL [13]. The energy resolution depends on the emission area of the sample and the diameter of energy aperture (EA) [13]. We evaluated the energy resolution of WAAEL using several apertures, and it was 0.5 % when the aperture diameter was 1 mm [13]. In the spatial image projection mode of DELMA, we can control the magnification by changing the voltages of the lens system. When higher energy resolution of the electron is required, the screen is taken away, and the electrons are introduced to the energy analyzer. The detail of WAAEL has been partially described elsewhere [10–15].

The biggest advantage of DELMA over DIANA is that it has both imaging and diffraction mode. The imaging lens mode is used to display a magnified image of the sample on screen. The transfer lens system can change the magnification. The diffraction lens mode is used to display angular distribution of photoelectrons on screen. The transfer lens system has the function of switching from imaging to diffraction mode. The transfer lens system is composed of four electrostatic lenses and twelve deflectors. We can use both imaging and diffraction mode by changing voltages of these electrostatic lenses.

The transfer lens system has three apertures for observing a clear magnified image and PIAD pattern from a specific area of a sample. In order to observe the image of the sample clearly, we use a contrast aperture (CA) shown in Fig. 1. A small CA can be used to limit the acceptance angle to obtain a clear magnified image of the sample. In order to observe the PIAD pattern from a specific area of the sample, that area is moved to the lens axis position while observing the entire image. Then, a small field aperture (FA-1 or FA-2) is inserted to select the area. In this experiment, however, the apertures (EA, CA, FA-1 and FA-2) were not used.

The acceptance angle of WAAEL was confirmed to be ±35° in a combination of WAAEL and energy analyzer [16]. In this paper, we report the first evaluation of the acceptance angle, the energy resolution and a magnified image of DELMA, using synchrotron radiation in SPing-8.

The test of DELMA was performed at the free port of BL07LSU in SPring-8. BL07LSU was constructed by the University of Tokyo to develop materials science with frontier spectrosocies using high brilliant synchrotron radiation [17]. BL07LSU produces a high brilliant soft x-ray beam by 8 segments of the parallel/perpendicular figure-8 undulators. BL07LSU has a free port station for researchers to set their own machines and to perform experiments with the high brilliant soft x-ray beam.

The base pressure of the chamber was ~ 1 × 10⁻⁷ Pa. Synchrotron radiation was incident from the direction 75° inclined from the central axis of the analyzer as shown in Fig. 1.

First, the imaging mode measurement system was evaluated by using DELMA part. We measured the magnified image from the SUS316 #100 mesh.

Then, the performance test of DELMA using synchrotron radiation was carried out as follows. First, the angular range of DELMA was evaluated using a special tool for measuring angular distribution pattern, which is shown in Fig. 2 (a). Figure 2 (b) is the design of the tool. These holes were separated by an interval of 10° step in vertical and horizontal direction. Two rows were added at ±45° in horizontal direction. We measured an angular distribution pattern using DELMA combined with the energy analyzer.

Finally, we used a the Ta plate for evaluating the total energy resolution. X-ray photoelectron spectroscopy (XPS) from Ta plate was measured with the whole system of DELMA combined with the energy analyzer.
FIG. 4: Schematic diagram of the photoelectron trajectories in the transfer lens. (a) The focus pattern is projected on the screen. This kinetic energy is used as the standard for normalization. (b) The diffused pattern appears when the normalized kinetic energy is around 0.98. (c) Angular distribution is projected on the screen at the normalized kinetic energy around 0.9. (d) Only the axial-trajectory electrons pass through the analyzer at the normalized kinetic energy of 0.7.

III. RESULTS AND DISCUSSION

To begin with, we introduce about the imaging mode using the DELMA part. First, the pass energy of WAAEL was adjusted to 702 eV which coincide to the Fe LMM Auger peak in the photoelectron spectrum as measured by the energy analyzer. The photon energy was set to 805.5 eV. A focused SUS316 #100 mesh sample image was displayed on the screen. Then the pass energy of WAAEL was set to 0.98% of the focusing condition. A diffuse image was displayed on the screen. The former image was divided by the latter image to remove the inhomogeneous detection efficiency of the system. The result is shown in Fig. 3. We have succeeded in measuring the magnified image of mesh using DELMA with improved quality compared to the previous work [13].

Figures 4 show schematic diagrams of the photoelectron trajectories in the WAAEL and the transfer lens parts. The screen position is at the sample position of the energy analyzer. Figure 4(a) shows some trajectories when the photoelectrons focus at the screen. When we use a thick x-ray beam, a real space image of the sample is displayed on the screen. We define the normalized kinetic energy using this kinetic energy. Figures 4(b)-(d) show trajectories when the photoelectrons have smaller kinetic energies. When the normalized kinetic energy is around 0.98, a diffused pattern is displayed on the screen. We can use this condition as the background image to remove the inhomogeneous detection efficiency of the screen as in the case mentioned earlier.

If the normalized kinetic energy is lowered, then the angular distribution is displayed on the screen, as depicted in Fig. 4(c). We evaluated the acceptance angle of DELMA combined with the energy analyzer using the special tool. Figure 5 shows the pattern from the tool observed by the energy analyzer. The measurement mode of the energy analyzer was set on transmission mode, in which the vertical axis corresponds to one line of the magnified image at the focal point of the energy analyzer. Horizontal axis is the kinetic energy of photoelectrons. The kinetic energy, normalized to the pass energy of WAAEL, is also shown as the upper abscissa of Fig. 5. In this experiment, we kept the voltages of WAAEL and lens system constant. The pass energy of WAAEL was 724 eV and photon energy was 708 eV. Photoelectrons were observed at the kinetic energy range from 500 to 700 eV.

The vertical width of the photoelectron pattern on the screen changed with the kinetic energy. The bright vertical line at the kinetic energy of 680 eV in Fig. 5 corresponds to the Ta 4f photoelectrons. The photoelectron vertical width was widest at the kinetic energy of 620 eV. The photoelectron width begins to decrease below the kinetic energy of 620 eV and disappears at kinetic energy about 500 eV. WAAEL functions as a high-pass filter because of the high negative potential at the center of WAAEL [13]. Because the negative potential is lowest at the axis, only the axial-trajectory electrons can go through WAAEL at the normalized kinetic energy of 0.7.

FIG. 5: The kinetic energy dependence of intensity distribution of photoelectron passed through DELMA measured using the energy analyzer.

FIG. 6: X-ray photoelectron spectrum (XPS) from Ta plate. Spin-orbit splitting of Ta 4f peaks are well resolved.
as shown in Fig. 4(d).

At kinetic energy around 620 eV, we can see a radial pattern as shown by the thin dotted lines in Fig. 5, the center of which exists at the pass energy of WAAEL of 724 eV kinetic energy. This radial contrast is formed by the photoelectrons passing through the holes of the angular distribution measurement tool. The radial pattern arises due to the chromatic aberration of WAAEL and lens system. The normalized kinetic energy value of 1.00 indicates that the photoelectrons focus at the focal point of the analyzer.

The acceptance angle of these seven red dotted lines corresponds to ±30° in Fig. 5. Although modulation is hardly seen, the intensity of the Ta 4f line extends out of ±30° as shown by additional three blurred dotted lines. This result indicated that the whole acceptance angle is ±45°, which agrees well with the designed value of ±45°.

Finally, we measured x-ray photoelectron spectra from the Ta plate to evaluate the total energy resolution of DELMA combined with the energy analyzer. Figure 6 shows x-ray photoelectron spectra from Ta plate at the photon energy of 708 eV. The pass energy of WAAEL was 736 eV. The slit width and pass energy of the hemispherical energy analyzer were 2.5 mm and 200 eV, respectively. Two spin-orbit-split peaks of Ta 4f5/2 and Ta 4f7/2 were clearly resolved in the photoelectron spectrum.

The total energy resolution $\Delta E_{\text{total}}/E_0$ is approximately defined by

$$\Delta E_{\text{total}}/E_0 = \sqrt{\Delta E_{\text{FWHM}}^2 - \Delta E_{\text{life}}^2 - \Delta E_{\text{hu}}^2 - \Delta E_{\text{T}}^2}/E_0,$$

where $\Delta E_{\text{FWHM}}$ is the full-width at the half maximum of a single peak, $\Delta E_{\text{life}}$ is the life time width of the 4f hole, $\Delta E_{\text{hu}}$ is the energy width of the photon, $\Delta E_{\text{T}}$ is the effect of temperature, and $E_0$ is the kinetic energy at the peak. The full-width at the half maximum of a single peak was 1.35 eV. The lifetime width of the 4f hole was reported to be ~0.1 eV [18]. The energy width of the photon was 0.16 eV. The effect of temperature at RT was estimated to the 0.1 eV. The measured total resolution of DELMA combined with energy analyzer was estimated to be 0.2% by using eq. (1). Hence, we succeeded in the evaluation of the total energy resolution of DELMA combined with the energy analyzer, which is better than DIANA and WAAEL itself.

**IV. CONCLUSION**

In conclusion, we reported the first results of DELMA combined with an energy analyzer using synchrotron radiation. We succeeded in measuring the magnified image by DELMA. The measured acceptance angle of the angular distribution pattern and the measured total energy resolution using DELMA combined with an energy analyzer were about ±45° and 0.2%, respectively. Although this acceptance angle was smaller than DIANA, the measured total energy resolution value is better than DIANA and WAAEL itself. These features will be improved by further adjustment of slit width, aperture diameter, parameters for the electron lens, and the sample position, suppression of magnetic field.

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