BL24XU
Hyogo ID

1. Introduction

BL24XU is known as the Hyogo ID beamline. It is a contract beamline designed by the Hyogo prefecture for industrial applications. It is a branched beamline employing a figure-8 undulator light source, a diamond (220) beam-splitting monochromator for branched line A, and a Si (111) double-crystal monochromator (DCM) for mainstream B. The end-station is specialized for high-resolution structural characterization by microbeams and imaging (Table 1).

Recently, we have begun actively promoting the use of informatics technologies such as machine learning for synchrotron radiation analysis. The informatics approach has the potential to rapidly derive the relationship among the structure, physical properties, and manufacturing processes by analyzing a number of specimens under different conditions. In addition, it may extract useful features from massive amounts of data such as two-dimensional spectrum mappings.

In FY2019, T. Ozawa et al., who belonged to Kobe Steel, investigated the corrosion process on steel surfaces by means of two-dimensional X-ray microbeam back-reflection Laue diffraction measurements. Adapting machine learning visualized the corrosion state distribution.

As a beamline upgrade in FY2019, the photon energy range available for experiments was expanded to the high energy side to promote applications of metal materials. Si(111) and Si(220) arranged crystals were installed into the DCM. The energy ranges, 5–37 keV in Si(111) and 8–60 keV in Si(220) settings, can be changed by simply translating them in the DCM system.

Efforts continue to develop new measurement methods. Bright-field X-ray topography, which was developed in recent years, is now available to industrial users. Here, we report its industrial applications as a research topic.

Table 1. Specifications of the measurement techniques in BL24XU.

Measurement techniques	**Structural Information**	**Spatial resolution**
Projection / imaging microscope / coherent diffraction CT	2D/3D image Field of view: 1 µm – 1 mm Absorption, refraction contrast (projection / imaging microscope) Absorption, phase contrast (coherent diffraction)	10 nm – 0.33 µm
Microbeam SAXS / WAXD / XRF	Periodic / aggregation structures of angstrom – several hundred nm Distribution of crystal grains Elemental mapping	0.5–5 µm
Bonse-Hart USAXS	Periodic / aggregation structures of 16 nm – 6.5 µm	bulk
Highly parallel microfocus diffraction, bright-field topography	Local strain, dislocation	0.5–30 µm (diffraction), 0.65 µm (topography)
Near ambient pressure HAXPES	Chemical state	30 µm

2. Bright-field X-ray topography

Bright-field X-ray topography under multiple diffraction conditions has many advantages such as rapid determination of the Burgers vector and less deformation of the image when the diffraction vector is changed [1]. For the last few years, this technique has been applied to hexagonal crystals such as GaN and AlN substrates for high-power electronic devices [2, 3]. In these crystals, the Burgers vector of dislocations existing in the crystal is *a*-type, *c*-type, or (*a*+*c*)-type.

The Burgers vectors of the characteristic dislocations were investigated from the topographic images of the dislocations on the basis of invisibility criterion of $\boldsymbol{g} \cdot \boldsymbol{b} = 0$, where $\boldsymbol{g}$ is a diffraction vector and $\boldsymbol{b}$ is a Burgers vector of the dislocation. First, the topographic images near the 6-wave excitation of $\boldsymbol{g}_{20\bar{2}0} (= -2\boldsymbol{g}_{m_2})$, $\boldsymbol{g}_{01\bar{1}0}\ (= \boldsymbol{g}_{m_1})$, $\boldsymbol{g}_{11\bar{2}0}\ (= -\boldsymbol{g}_{a_3})$, $\boldsymbol{g}_{2\bar{1}\bar{1}0}\ (= \boldsymbol{g}_{a_1})$, and $\boldsymbol{g}_{1\bar{1}00}\ (= \boldsymbol{g}_{m_3})$ were acquired for the hexagonal crystals. In addition, topographic images of $\boldsymbol{g}_{m+c}$ and $\boldsymbol{g}_{m-c}$ were acquired to distinguish between the *a*-type and (*a*+*c*)-type dislocations. For example, $\boldsymbol{g}_{m+c}$ orthogonal to $\boldsymbol{b}_{a_1+c}$ should be $\boldsymbol{g}_{m_1}$, $\boldsymbol{g}_{-m_2-c}\ (= -\boldsymbol{g}_{m_2+c})$, and $\boldsymbol{g}_{m_3-c}$. On the other hand, $\boldsymbol{b}_{a_1}$ is orthogonal to $\boldsymbol{g}_{m_1+c}$, but not to $\boldsymbol{g}_{-m_2-c}$ and $\boldsymbol{g}_{m_3-c}$.

Figures 1(a)–(e) show a series of the topographs of a GaN substrate with $\boldsymbol{g}_{01\bar{1}0}$, $\boldsymbol{g}_{11\bar{2}0}$, $\boldsymbol{g}_{10\bar{1}0}$ (adopted here instead of $\boldsymbol{g}_{20\bar{2}0}$ to gain a larger structure factor for clearer dislocation images), $\boldsymbol{g}_{2\bar{1}\bar{1}0}$, and $\boldsymbol{g}_{1\bar{1}00}$, respectively. Various dislocation images were taken at the same area. All the topographs except that in Fig. 1(a) show dislocation A, while dislocation B appears in all the topographs except that in Fig. 1(c). Dislocation C is visible in all the topographs except that in Fig. 1(e). Combined with the results of the topographic images of $\boldsymbol{g}_{m+c}$, the Burgers vector of the dislocation of A is $\boldsymbol{b}_{a_1} = \frac{1}{3}[2\bar{1}\bar{1}0]$. The multi-wave bright-field X-ray topography shown in this report should be applicable to various single crystals used for electronic devices, especially to investigate crystal defects influencing device performance.

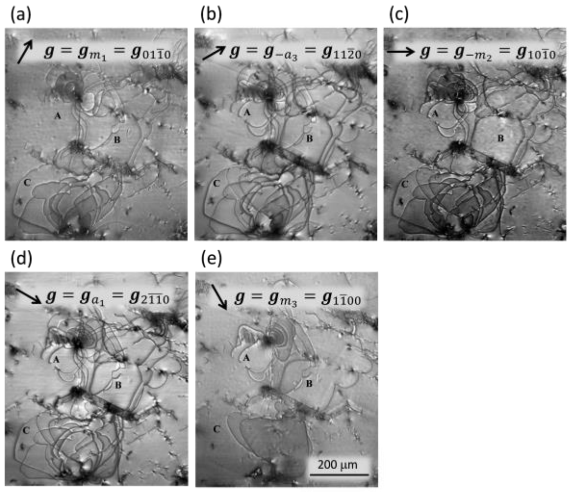

Fig. 1. Topographs of basal plane dislocations taken by five reflections, $\boldsymbol{g}_a$ and $\boldsymbol{g}_m$. Diffraction vectors are (a) $\boldsymbol{g}_{m_1}$, (b) $\boldsymbol{g}_{-a_3}$, (c) $\boldsymbol{g}_{-m_2}$ (instead of $2\boldsymbol{g}_{-m_2}$), (d) $\boldsymbol{g}_{a_1}$ and (e) $\boldsymbol{g}_{m_3}$, all lying parallel to the (0001) plane.

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