Dramatic improvement in the throughput of X-ray topography

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Abstract

Rigaku launched a high-speed X-ray topography system with the improved throughput of 10–20 wafers/hour (3–6 min/wafer). High-speed image acquisition is achieved using an uncollimated divergent beam and the HyPix-3000HE hybrid pixel detector. This technical note explains two major features that contribute to this improvement by dramatically reducing the time for alignment and the travel distance of the specimen to obtain topographic images of the whole area. This high-speed X-ray topography system is poised to play a key role in the quality control of wafers.

1. Introduction

The global notion of sustainable development goals evokes a huge demand for high-quality single crystalline materials and wafers, which are indispensable for highly efficient devices in various fields such as power electronics. To improve and maintain the quality of materials, development of investigation techniques is indispensable. X-ray topography (XRT) is one of the non-destructive analysis tools used to visualize defects in single crystalline materials. XRT has advantages over other inspection techniques used to evaluate various lattice defects such as dislocations because it captures signals that originate solely from lattice strain in a crystal. Rigaku launched a high-speed XRT system equipped with a hybrid pixel detector (HyPix-3000HE) to support those who are investigating the distribution of crystalline defects of single crystalline materials and wafers by providing a means to acquire topographic images easily and quickly. This note describes the technical features behind the improvement as well as its application to 4H-SiC wafers, whose quality is one of the largest concerns for those working on power devices made of 4H-SiC.

2. The High-speed XRT System with a HyPix-3000HE Detector

One of the challenges for conventional laboratory XRT systems, including our XRTmicron (1), (2), is the time required to take a topographic image. In quality control, several tens of minutes is too long for the total inspection of a wafer. Our new system has overcome these difficulties and achieved the throughput of 10–20 wafers/hour. Two important features contribute to this high throughput: alignment-free measurement and fast and wide-area data acquisition. Our hybrid pixel detector HyPix-3000HE—with the following three features: a) large detection size of 77.5 mm × 38.5 mm, b) high maximum frame rate of 120 fps, and c) high detection efficiency on Mo $K\alpha_1$ radiation, which is typically used for XRT measurement with transmission geometry—plays a key role in achieving the above-mentioned improvement. We will describe how the new system applies the features of HyPix-3000HE by contrasting the newly developed image acquisition scheme to conventional ones.

2.1. Alignment-free XRT imaging

A diffraction signal is available only when an X-ray beam irradiates a specimen in an appropriate geometrical direction, fulfilling the diffraction condition. With conventional systems, alignment is necessary since the X-ray beam is collimated either by an incident slit or a multilayer mirror, as shown in Figure 1. Alignment consists of the following two processes: (A) adjusting the position of the specimen relative to the incident X-ray beam, and (B) evaluating the lattice plane curvature of the specimen. The former includes iterative scans of omega (the incident angle between the X-rays and the specimen) and phi (the azimuthal angle of the crystal versus the X-ray source), which typically takes about 7 minutes. The latter alignment is almost indispensable to obtain homogeneous topographic images since the appropriate incident angle to the specimen may differ from one location to the other due to a curved lattice plane, originating from a variety of features such as crystal growth, dicing, and the weight of the specimen itself. This alignment takes more time than alignment (A)—about 20 minutes for a 150-mm wafer—since it requires performing omega scans at various positions on the specimen, causing poor wafer throughput.

The XRTmicron with a HyPix-3000HE detector has an option to utilize divergent X-rays. A divergent incident X-ray beam shoots the sample during the measurement with HyPix-3000HE. In other words, X-rays are irradiated onto a specimen at a variety of incident angles, compensating its tilt, curvature, and the azimuthal angle against the stage. Topographic images of one 150-mm 4°-off 4H-SiC wafer taken with the $11\bar{2}0$ reflection, for example, are available even if the off-cut

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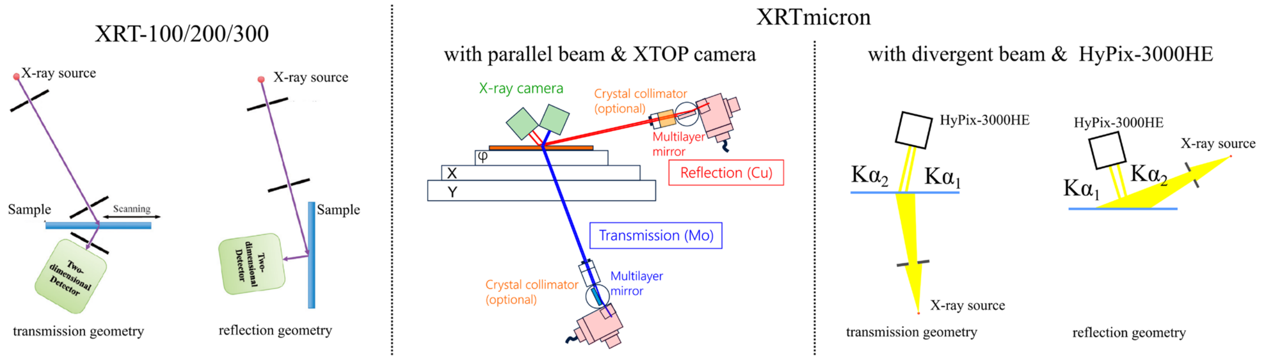

Fig. 1. Schematic images of XRT systems launched by Rigaku.$^{(1)}$

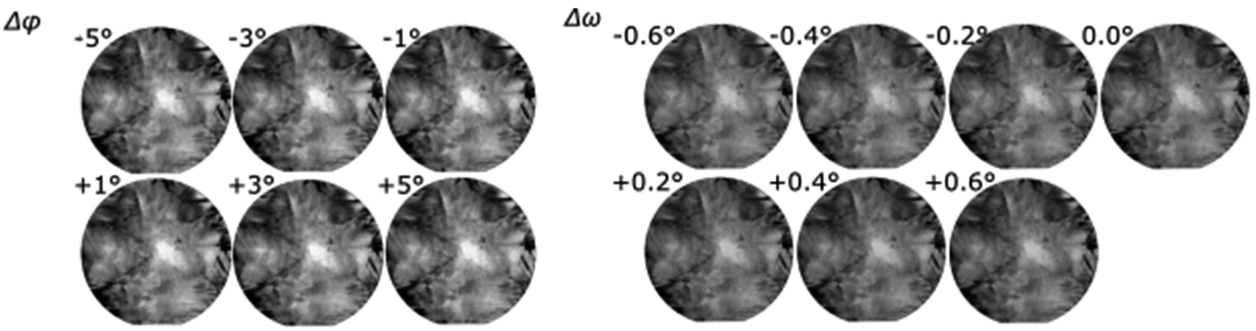

Fig. 2. XRT images of the 11$\bar{2}$0 reflection of a 150-mm 4H-SiC wafer taken at various φ (azimuthal angles) and ω (incident angles).

angle varies by ±0.6° and the flat/notch angle varies by ± 5° (Figure 2). With an autoloader and a wafer aligner, provided the accuracy of the notch/flat is high enough, the system can measure without performing any alignment procedures to obtain an XRT image. This alignment-less feature contributes to the improved throughput of wafer inspection.

Without collimating the incident beam, the system needs solutions for a couple of challenges. One is the diffraction of another characteristic X-ray whose wavelength is close to that of the characteristic X-ray with which we intend to create a topographic image. An example of this is Kα_1 and Kα_2 radiation. Our conventional laboratory XRT systems avoid such stray diffraction signals by applying a collimated beam, fine alignment, and a slit in front of the detector. The alignment-free high-speed XRT configuration does not employ any of these; therefore, the diffraction signal from unwanted wavelengths is recorded by the HyPix-3000HE. To ignore these extraneous diffraction signals, we selectively extract the signal of interest from all the diffraction patterns acquired during the scan$^{(3)}$ (Figure 3) prior to the construction of a topographic image. This signal extraction can be thought of as a "virtual slit" at the detector$^{(4)}$. This "virtual slit" approach has a huge advantage compared to a mechanical slit since the shape and the size of the slit is adjustable flexibly and automatically. For example, a diffraction pattern taken at reflection geometry with Cu Kα_1 radiation is curved over the detection area and its curvature varies depending on the measurement geometry. With the "virtual slit," it is possible to extract the entire curved diffraction pattern regardless of the geometry, which is not possible with any mechanical slits. Thus, the alignment-free nature of the high-speed XRT system is applicable to a wide range of geometries, from transmission to reflection, for various specimens.

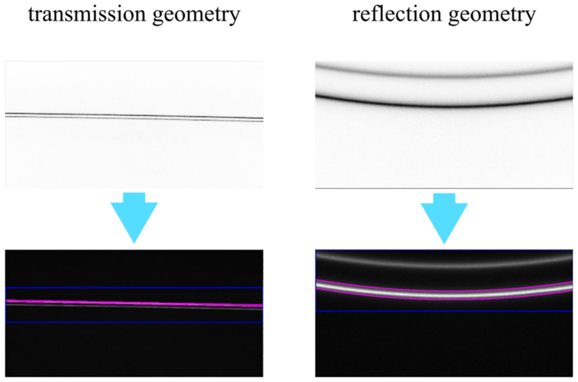

Fig. 3. "Virtual slit" extracting a diffraction signal of interest. This system automatically calculates the region to extract from the original diffraction pattern, shown as the area between the two pink lines at the bottom of each image.

2.2. Making full use of HyPix-3000HE

The other important features for faster image acquisition are the higher speed of the scan and the shorter total travel distance of a specimen per topographic image. Both features are achieved using our hybrid pixel detector, HyPix-3000HE. The measurement

Table 1. Features of the Rigaku's XRT systems.

	XRT-100/200/300	XRTmicron	
		Multilayer mirror & XTOP	HyPix-3000HE
Incident optics	Double slit	Multilayer mirror	slit
Incident X-rays	Quasi-parallel beam	Quasi-parallel beam (divergence angle ~0.5 mrad)	Divergent beam
Detector (resolution)	IP (>50 μm) XTOP (5.4 μm)	XTOP (5.4 μm)	HyPix-3000HE (100 μm)
Width of the detector	IP：>100 mm XTOP：18 mm	18 mm	77.5 mm
How to extract diffraction signal	Alignment	Alignment	"Virtual slit"
Data acquisition	IP：Development required XTOP：digital image	Digital image	Digital image

of a topographic image consists of simultaneous specimen motion and data acquisition; therefore, the frame rate of the detector limits the speed of the scan. With a frame rate of 120 fps, the high-speed XRT system with HyPix-3000HE achieves a scan speed of at least 600 mm/min. Here, the zero dead-time feature(5) of HyPix-3000HE benefits us. The specimen is allowed to move continuously during data acquisition since there is no need to wait for the detector to acquire new data. The diffraction signal from the specimen is recorded seamlessly by the HyPix-3000HE, being integrated into the generated topographic image without any loss of signal and time. The width of the HyPix-3000HE detector contributes to the reduction in travel distance of the specimen to obtain a topographic image. As shown in Table 1, the width of the HyPix-3000HE is 77.5 mm, which is more than 4 times wider than the XTOP camera used on the conventional XRTmicron system. Despite the longer specimen-detector distance compared to the conventional XRTmicron, which reduces the actual probe width on the specimen to at most 65.0 mm, the total travel distance is reduced by two-thirds. For example, the required travel distance to scan a 150-mm-wafer is ca. 500 mm with the high-speed XRT system, while the previous system requires ca. 1700 mm.

By combining all the features described in this section, we achieved throughput of 10–20 wafers/hour. Table 1 compares the features of our XRT systems from various perspectives. The table clearly illustrates how the new high-speed XRT system is advantageous over our conventional systems in its throughput. It should be noted that the high-speed XRT system and the conventional high-resolution XRT system can be combined in a single system, giving users the opportunity to perform both fast imaging and high-resolution imaging.

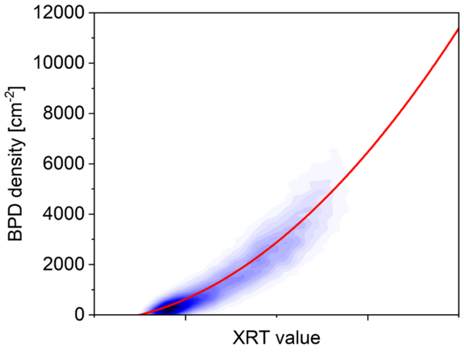

Fig. 4. A calibration curve between the gray values of the XRT image (horizontal axis) and the BPD density evaluated by KOH etching (vertical axis) of a 4°-off 4H-SiC wafer.

3. Application: Basal Plane Dislocation (BPD) Density Analysis of 4H-SiC Wafers

One of the trending applications of high-speed XRT imaging is the quantification of BPD density in 4°-off 4H-SiC bare wafers. BPD is a perfect dislocation on the basal plane of a SiC crystal and is known as a source of stacking faults during the operation of power devices, causing degradation of these devices(6). Therefore, reducing and controlling the amount of BPDs is of keen interest to wafer manufacturers. Recently, C. Kranert *et al*. from Fraunhofer IISB have developed an analysis technique to evaluate the quantity of BPDs from the dislocation contrast of $11\bar{2}0$ topographic images. They found a correlation between the number of pits of a BPD after KOH etching and the topographic image intensity of the $11\bar{2}0$ reflection of 4°-off 4H-SiC bare wafers (Figure 4) (7), (8). By creating a calibration curve between the diffraction intensity obtained as a topographic image and the BPD density derived through etching, the BPD density of a wafer is derivable through XRT. With the high-speed XRT system and this calibration technique, the BPD density of a 4°-off 4H-SiC 150-mm bare wafer can be obtained within 5 minutes, including loading and unloading of the wafer. Compared to the conventional XRTmicron with XTOP camera, which takes approximately 60 minutes to complete the image acquisition, the high-speed XRT system has a great advantage in evaluating BPD density. This speed is almost comparable to other non-destructive dislocation quantification techniques such as photoluminescence. The analysis software implementing the technique mentioned above is now under development at Fraunhofer IISB and will be accessible with Rigaku's XRTmicron control software, which will be one of the key collaboration outcomes of the Center of Expertise for X-ray Topography, cooperation between the Rigaku and Fraunhofer IISB.

4. Summary

This technical note described the background of the new XRT imaging process with a high throughput of 10–20 wafers/hour. High-speed image acquisition is achieved by the use of a divergent beam and the hybrid pixel detector HyPix-3000HE. The "virtual slit" approach to extract the signal of interest from the raw diffraction signal has enabled alignment-free XRT imaging for a variety of reflections. One of the striking applications developed by Fraunhofer IISB is the quantification of BPDs in a 4°-off 4H-SiC wafer, which may open up a way to use this high-speed image acquisition technique to the quality control of 4H-SiC wafers. It should also be noted that the fast XRT system described in this technical note can be implemented on our conventional high-resolution XRTmicron system. This system offers a combination of screening and detailed investigation in a single apparatus, which benefits R&D users as well. We also believe that the application of this high-speed XRT system will be of great use in investigating defects/dislocations in single crystalline materials (e.g., Si, sapphire, and quartz), as well as in wafers after processing.

Acknowledgement

I'd like to gratefully acknowledge the kind courtesy of Dr. C. Kranert at Fraunhofer IISB for allowing me to present the correlation curve between the gray value of an XRT image and the corresponding BPD density evaluated by KOH etching in Figure 4.

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