X-Ray Wave Guide and its Possible Application to Surface Analysis; X-Ray Traveling Waves

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We propose a novel surface analysis method, "X-ray traveling waves using an X-ray waveguide". The traveling wave is an opposite concept of the standing wave. The X-ray standing waves have been used for the analysis of surfaces by total reflection X-rays. The traveling wave is the X-rays refracted at the surface, and this novel method is to detect the refracted waves at the cross-section of a specimen. Such a traveling wave shows strange features, the origins of which are still not clarified, but also shows a similarity to the "Yoneda wing" phenomena.

X-rays are totally reflected by a flat interface at the angle of grazing incidence. The total reflection X-rays have been used for many kinds of surface analysis methods, such as the total reflection X-ray fluorescence analysis (TXRF) [1], grazing incidence X-ray diffraction (both Seemann and in-plane arrangements) [2], reflectivity [3], total reflection X-ray absorption spectroscopy [4], and the total reflection X-ray photoelectron spectroscopy [5-7]. When we measure the reflectivity or other secondary quanta excited by the total reflection X-rays, we can sometimes observe fringes or an interference effect between the incoming and outgoing X-ray beams. This interference fringe is due to the formation of the standing waves. The standing wave is formed normal to the surface. If the X-ray beam once penetrates into the surface and then reflected inside the material, the X-ray beam travels at the direction parallel to the surface, as is schematically depicted in Fig. 1.

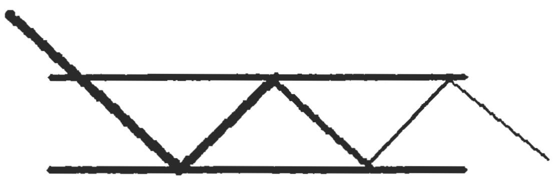

Fig. 1 Schematic illustration of a traveling wave.

By using this total reflection, we can make a traveling wave of X-rays between two flat layers. We have measured the reflectivity of many kind of modified flat surfaces, such as a silicon wafer surface where gold was vacuum evaporated [8,9], a Ta and Ti multilayer on silicon wafer, and natural oxide layer or organic film on silicon wafer [10,11].

The measurements were performed with a conventional copper target X-ray tube; the X-rays were collimated less than 0.5 mm diameter. The X-ray detectors we used were at first Si(Li) solid state detector, but later a Geiger-Müller counter with a thick aluminum filter was used (Fig. 2). A Geiger-Müller counter was easy to be saturated. To avoide this saturation, we used the aluminum to attenuate the X-rays. The reason we used a Geiger-Müller counter was that we needed a wide detection area; the sample was rotated but the detector was fixed.

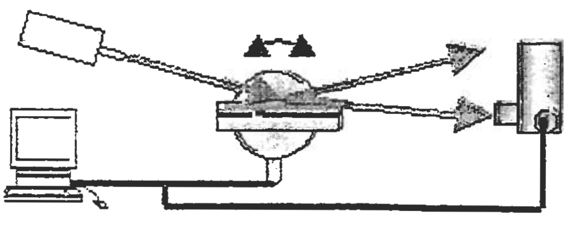

Fig. 2 Schematic illustration of the experimental setup.

Afterwards, we used an SDD (silicon drift detector) assembled by OURSTEX, Hirakata, Japan, which had a high energy resolution as an SSD (solid state detector) and we could rotate the detector with twice the rotating angle of the specimen or any other relation we needed.

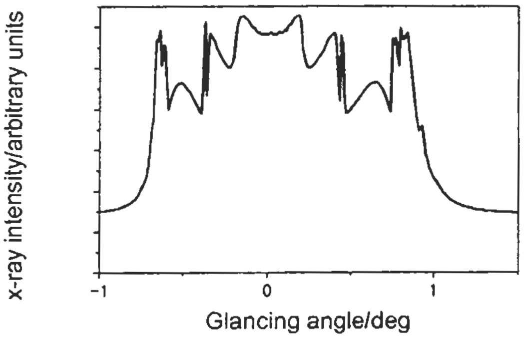

Fig. 3 The reflectivity of Au islands on Si wafer.

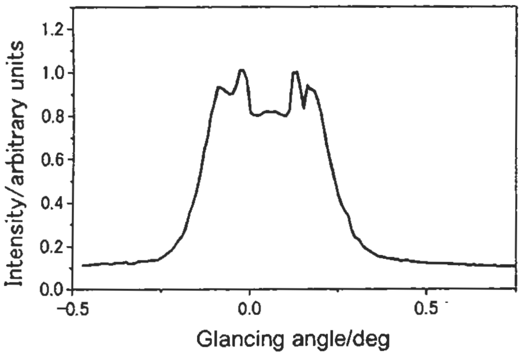

Fig. 4 The reflectivity of a Ta/Ti/Ta/Ti/Si multilayer.

We found a similar symmetric pattern in totally reflected X-ray intensity as shown in Figs. 3 and 4 for any kinds of specimens, where the glancing angle means the relative angle between the sample surface and the incident X-ray beam. Here the X-ray intensity we measured was the total intensity without selection of the angle or the energy. We cannot reproduce these symmetric patterns from any kinds of numerical simulation (Fig. 5), which we coded with a computer program for reflectivity calculation [12]. Though the relation between these patterns and the Yoneda wing [13] has not yet been clarified, they look quite similar. Horiuchi *et al.* [14,15] pointed out a similarity between the present traveling wave and the Yoneda wing.

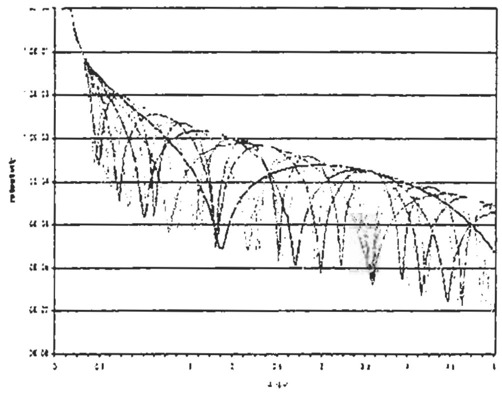

Fig. 5 Calculated example for a multilayer, W(0.5nm)/B_4C(0.5-5.0nm with 0.5nm step) / W(0.5nm)/Si was assumed for 10 keV incident X-rays.

We believe these strange phenomena are related to some kinds of surface traveling or propagating X-ray waves. When the surface roughness becomes higher, the pattern becomes more complicated. Similar traveling waves were calculated theoretically by Ebel *et al.* [16] and experimentally by Pfeiffer *et al.* [17]. The origin of the symmetric pattern may be mostly the specimen edge effect; the edge of the silicon wafer may have acted as an X-ray prism, and some kinds of the refracted X-rays were observed. X-rays traveling along with the surface may have been detected in such a symmetric pattern also.

Anyway, this kind of symmetric pattern was very sensitive to the surface state of the specimen and the reproducibility of observing the same pattern was remarkably bad. This indicates that the measurements of this kind of symmetric pattern will become a powerful tool to characterize a surface state in the near future.

The incident beam sometimes hit the edge of the sample and sometimes not. The intensity of the negative angle of incidence were similar to that of the positive angle, which meant that the X-ray path of negative angle was mostly same as that of the positive angle. Thus the X-rays were glancing at the edge of the silicon wafer sample. Since the X-rays would be attenuated strongly in the silicon wafer, the depth of the edge where X-rays were effectively penetrated was estimated to be of the order of micrometers. It was found, if the details of Figs. 3 and 4 are checked, that the positive angle side was more elongated than the negative side. This was the general rule of the present symmetric pattern. The origin, *i.e.* the angle = 0, does not always coincide the center of the graph. Though the reproducibility of the pattern was very worse as was described above, the pattern had almost every time a symmetric pattern as are shown in Figs. 3 and 4, for examples.

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