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Characterization of a diamond crystal x-ray phase retarder

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An x-ray phase retarder plate based on a diamond single crystal diffracting in the asymmetric Laue geometry has been characterized at the X25 wiggler beamline at the National Synchrotron Light Source. The forward diffracted (transmitted) beam, using the (111) Bragg planes in a 0.5 mm thick wafer with a (001) surface normal, was employed. A polarization analyzer based on a GaAs(111) crystal oriented to diffract the (222) and a different reflection simultaneously was used to determine the Stokes–Poincaré polarization parameters of the beam transmitted by the diamond phase plate, at several settings of the diamond about its (111) rocking curve. At 7.1 keV, the phase plate performed as expected and it was proven possible to produce, with the plate, an almost completely left- or right-handed circularly polarized x-ray beam from a linearly polarized incident beam. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1447586]

I. INTRODUCTION

Perfect single crystals have proven to be effective x-ray phase retarders.[1,2] X-ray birefringence occurs in a perfect crystal which is oriented in the vicinity of a Bragg reflection, giving rise to phase shifts between the σ and π polarization components of the beams propagating through the crystal. This results in forward-diffracted (transmitted) and diffracted beams whose polarization ellipticity and handedness can be adjusted according to the crystal thickness and angular deviation from the Bragg condition. In recent years the availability of good quality diamond crystal wafers has made them popular for use as phase retarders,[3,4] owing to diamond's small absorption coefficient (in comparison with silicon and germanium) which allows wafers of reasonable thickness (the order of 1 mm) to be employed at conventional x-ray energies (the order of 10 keV) for forward-diffracted beams whose directions do not change as the energy is scanned, and for angle settings somewhat removed from the Bragg condition where the birefringence changes more slowly with angle.[5] These wafers can act as phase retarders in either Laue[6] or Bragg[7] geometries.

This article describes the performance of a diamond crystal wafer diffracting in asymmetric Laue geometry. The transmitted beam's polarization state was determined through measurement of its Stokes–Poincaré polarization parameters using an analyzer based on a GaAs crystal oriented in a multiple beam diffraction condition.[8] This kind of characterization of a phase retarder's performance has been carried out previously.[9–11] Here measurements have been made at several angle settings of the diamond(001) wafer about its (111) Bragg reflection rocking curve.

II. SETUP AND PROCEDURE

The experiment was performed on the X25 wiggler beamline at the National Synchrotron Light Source (NSLS). The beam incident upon the phase plate was conditioned using a vertically reflecting toroidal focusing mirror followed by a vertically diffracting double Si(111) crystal monochromator set to diffract 7.1 keV. The beam divergences were 0.2 mrad horizontally and 0.15 mrad vertically, the energy spread of the beam was 4 eV, and it was $>98\%$ linearly polarized horizontally.

The diamond wafer used for the phase plate was 4 mm $\times 4$ mm$\times 0.5$ mm thick in dimension, with a (001) surface normal. Its measured mosaic spread was 8 arcsec. It was oriented to diffract the incident beam using the (111) Bragg reflection in asymmetric Laue geometry, chosen such that the angle of incidence relative to the wafer's entrance surface (79.8°) was larger than the angle of emergence of the diffracted beam relative to the exit surface (29.7°). Thus the thickness of crystal traversed by the transmitted beam was 0.51 mm, whereas Laue diffraction employing the opposite asymmetry (angle of incidence smaller than angle of emergence) would present a thickness of 1.01 mm to be traversed,

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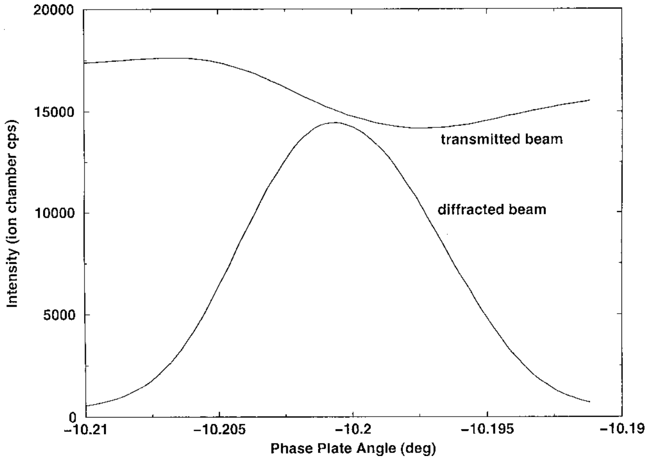

FIG. 1. Diamond(111) rocking curve profiles for the transmitted (top) and diffracted (bottom) beams. The abscissa represents the angle of the incident beam relative to the wafer surface normal. The ordinate scale for the diffracted beam has been magnified by a factor of 10.

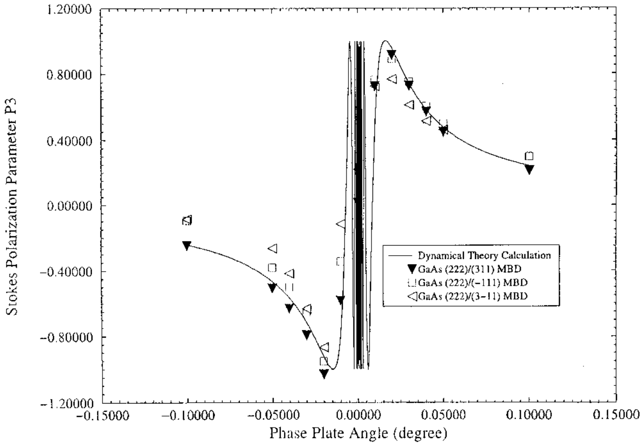

FIG. 3. The measured P_3 data for the different three-beam diffraction conditions of the GaAs analyzer and for different relative angle settings of the diamond(111) rocking curve are compared with a calculation based on dynamical diffraction theory.

and lower transmission as a result. Note that use of the transmitted beam in the Bragg geometry case, e.g., use of the (111) Bragg reflection in a wafer with a (111) surface normal, would present an even longer path length for this beam to traverse the wafer, if of the same thickness, and consequently even lower transmission. The transmission of the phase plate described here, away from the Bragg condition where it functions as a circular polarizer, is about 32% for the experimental conditions employed.

In order to present equal incident σ and π polarization components to the phase plate, the scattering plane was rotated about the incident beam direction by 45°. Ionization chambers were used to monitor the intensities of the incident, diffracted, and transmitted beams. Diffracted and transmitted beam rocking curves are shown in Fig. 1. The full width at half maximum is 0.008° for the diffracted beam. This is due to the beam divergence and the dispersion between the Bragg reflections of the upstream silicon monochromator and the diamond phase plate.

To analyze the polarization state of the transmitted beam, a GaAs(111) crystal mounted on a four circle polarimeter specially constructed for multiple beam diffraction analysis of beam polarization was used.[12] For all three-beam measurements, the (222) Bragg reflection served as the main one and the chosen simultaneous "detour" Bragg reflection was (311), (−111), or (3−11). A complete determination of the Stokes–Poincaré parameters P_1 (the degree of σ and π linear polarization), P_2 (the degree of ±45°-tilted linear polarization), and P_3 (the degree of left- and right-handed circular polarization) requires measurement of the integrated two-beam intensities [i.e., just the (222) reflection active] for scattering plane orientations (relative to the vertical) χ of 0°, 90°, and ±45°, plus the measurement of an azimuthal ϕ angle scan through the three-beam condition.[13] The degree of unpolarized radiation P_0 is then determined by

$$P_0 = 1 - (P_1^2 + P_2^2 + P_3^2)^{1/2}.$$

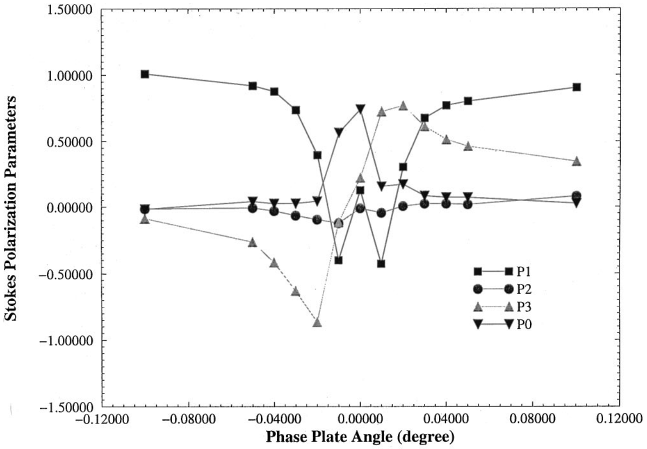

FIG. 2. The measured Stokes–Poincaré polarization parameters are shown for different relative angle settings of the diamond(111) rocking curve.

III. RESULTS

Plotted in Fig. 2 are the measured Stokes–Poincaré polarization parameters at different (111) rocking curve relative angle settings of the diamond phase plate. The P_3 values shown represent the average of the values determined from the three different three-beam measurements at each rocking curve angle setting. P_3 was determined to be −0.95 and 0.87 at relative angles of −0.02° and 0.02°, respectively, indicating highly circularly polarized radiation at those settings.

Finally, Fig. 3 compares the $P3$ values determined from each of the three-beam measurements with a calculation based on dynamical diffraction theory for the transmitted beam in the Laue geometry.[2,14] Zero beam angular divergence was assumed in the calculation, which is a reasonable approximation away from the Bragg reflection where the birefringence varies slowly with angle, but not a good approximation at the center of the rocking curve where the birefringence varies rapidly. The calculation agrees well with the data at and beyond ±0.01° from the rocking curve center and appears to indicate that the maximum degree of circular polarization occurs at relative angles close to ±0.015°. Near the center of the rocking curve, the polarization state varies rapidly with angle, and will be poorly defined in the transmitted beam if the incident beam has finite divergence. This explains why the unpolarized fraction P_0 experimentally appears to predominate at the center of the rocking curve in Fig. 2. It represents an average of many polarization states.

IV. SUMMARY

The setup and polarization state characterization, using multiple beam diffraction, of an x-ray phase retarder plate based on a (001) oriented diamond crystal wafer diffracting the (111) Bragg reflection in the asymmetric Laue geometry have been described. Experiment and theory agree well. The use of (001) oriented diamond crystal wafers (the most readily available diamond crystals) and the Laue geometry (for which alignment is relatively straightforward and for which the incident beam is generally confronted with a minimum of crystal material to traverse, as compared with the Bragg geometry) facilitate the application of diamond crystals as x-ray phase retarders. For the particular phase plate described here, a circular polarization helicity switching mechanism, based on a piezoelectric bending mount, has been fabricated.

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