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Production of Coherent Bremsstrahlung Radiators from CVD Diamond

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ABSTRACT: Abstract must be short enough to appear in this page toghether with title, authors, their addresses and keywords.

KEYWORDS: Coherent Bremsstrahlung; Diamond.

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1. Introduction

1.1 Requirements

The high energy, high intensity, polarized photon beam in the new Hall D facility at Jefferson Lab will be achieved using Coherent Bremsstrahlung (CB) of 12 GeV electrons from the CEBAF accelerator in a diamond radiator. The requirement of coherent scattering on the lattice places a constraint on the scattering plane orientation with respect to that of the electron trajectory. Significant variations in the scattering plane orientation across the diamond surface (mosaic spread) or in the electron trajectory due to multiple scattering or beam divergence, result in degradation of CB fraction in the photon output and consequently the photon beam polarization fraction. Thus, what is required is a diamond radiator that is thin enough to minimize multiple scattering while remaining strong enough to last in a high intensity beam and maintain small mosaic spread. The requirements set for the Hall D facility, in light of the physics requirements of its flagship experiment, GlueX, and the expected electron beam characteristics are 15 μr mosaic spread and 20 μm thickness of the diamond radiator.

Synthetically-produced diamonds using the processes of High-Pressure High-Temperature (HPHT) and Chemical Vapor Deposition (CVD) are known to result in crystals with mosaic spread that meets the above requirement. However, thinning and polishing of samples that usually emerge from these process as 300 μm-thick wafers without degrading their mosaic spread is a significant challenge. To date, mechanical techniques of diamond thinning have resulted in significant internal strain and consequent warping of the wafer, resulting in mosaic spread orders of magnitude above the specified maximum. However, new techniques have emerged: chemically-assisted lapping and ultraviolet laser-oblation.

Paramount in the search for good diamond radiators is a technique for their characterization: the material must be assessed before it is placed in the accelerator beamline. Transmission-mode X-ray scattering is thought to be the most thorough for assessing the mosaic spread of a crystal. A sample is oriented with respect to a monochromatic hard X-ray beam to meet the Bragg condition for a desired crystal plane. The distribution in angle over which this condition is met is determined by rocking the sample in the angle of scattering and measuring the scattered X-ray output. This "rocking curve" measurement can be performed on the entire wafer at once by illuminating the entire sample and measuring the scattered radiation with a high resolution camera X-ray camera. The mean angle at which the Bragg condition is met is determined from the centroid of the local rocking curve, while the local mosaic spread is determined from its width. The centroid and width of the rocking curve are often functions of position on the diamond wafer as a result of variations in crystal quality, local strains and macroscopic wafer curvature. Since the electron beam spot on the crystal in Hall D will be of several mm^2, the photon beam characteristics will be sensitive to variations in rocking curve parameters across the crystal surface. Thus the requirement on the mosaic spread dictates an upper bound on the whole-crystal rocking curve: a convolution of the centroid position distribution with the local rocking curve.

2. Characterization

2.1 Methods

The beam line C at the Cornell High Energy Synchrotron Source allows placement of samples 14.5 m from the bending magnet. To minimize the angular dispersion, increase the beam size and pick out the 15 keV component, a double bounce silicon monochromator is assembled upstream of the experimental hutch using the (3,3,1) planes. Samples are mounted on a thin stretched mylar membrane that is attached to a four-axis goniometer with arc-second resolution in the Bragg angle.

In order to verify the configuration of the silicon monochromator and other aspects of the setup, another silicon crystal wafer was used as a sample. It was oriented to study the (3,1,1) planes to check the matching with the monochromator. Being a sample of well-known crystal lattice orientation across its surface, this procedure offered a check on the distortions introduced by the sample holder. This procedure demonstrated that instrumental resolution in the rocking curve of less than $10\,\mu$r was achieved but that the variation of the rocking curve centroid along the wafer surface is many times this quantity due to the warping by the stretched mylar mount.

Full crystal rocking curves of all the samples were then examined in two orthogonal orientations (2,2,0) and (2,-2,0) in order to build a map of local plane normal vectors. The root mean square distribution of their orientations represents the principle figure of merit for a diamond radiator sample.

Complementary techniques to X-ray-based characterization involve visible light interferometry. A Michelson interferometer is easily assembled on the bench to image interference patterns between three light fronts: the reference mirror and the front and back surfaces of the wafer. Analysis of the complex three-wave interference pattern that results from these measurements requires fitting an interference model to the recorded intensity. Moments of the diamond surface curvature functions are adjusted with the fit driven by a "simulated annealing" minimum search. This technique is necessary because the objective space in this minimization search has many local minima, corresponding to the various ways of simulating the intensity map due to the inherent phase ambiguity in this problem.

Another optical surface characterization device used is the Zygo 3-D Optical Scanning Interferometer Profilometer: a device employing white light interferometry to profile the surface. The short coherence length of white light allows examination of the wafer surface in terms of contours in small (??) steps.

2.2 Tested Samples

Four varieties of thinned diamond wafer samples were tested at the Cornell facility:

1. (2) virgin Element Six electron grade wafers
2. (4) virgin Element Six "plates"
3. (1) 9 μr SINMAT-thinned wafer from an Element Six "plate"
4. (1) 10 μr diamond procured directly Element Six (unknown thinning technique)

The characterization of the virgin samples provided the reference parameters against which their characteristics will be judged after thinning. A comparison of electron grade and the cheaper "plates" was also of interest. Finally, the performance of current thin diamond candidates provide a guide to the current degree of development of the thinning techniques.

3. Results

Figures 1 and 2 show the rocking curve width and centroid (respectively) as a function of position on the non-electron grade "plate" surface. Figures 3 and 4 represent the same for a thinned "plate". Comparing these sets, it is evident that apart from "hot spots" where significant structural damage must have occurred during thinning, the local crystal structure maintains small mosaic spread after thinning. However, the centroid of the rocking curves, corresponding to the local normal to the scattering planes, is broadly distributed across the surface of the thin sample. The virgin thick plate appears to maintain the crystal orientation rigidly, whereas the thinned diamond loses its tensile strength and develops internal strains that result in a curved natural shape. It is this contribution that is the primary challenge in developing a thin diamond radiator with narrow whole crystal (averaged) rocking curve. Similar conclusions may be drawn from the 10 μm, Element 6-thinned diamond. While the local crystal structure is sufficiently good across most of the surface, the wafer lends itself to bending, therefore spreading the crystal plane orientation widely across the diamond surface. So, the average over a spot of several mm^2 would result in an unacceptably-wide mosaic spread.

4. Conclusion

The candidate Coherent Bremsstrahlung diamond radiators examined in the X-ray beam of the CHESS beamline C suggest that the principle contribution to the whole-crystal mosaic spread for thinned diamonds is the warping of the flexible and internally-strained wafers. This result poses a challenge to the development of the needed $\sim$20 μm diamond radiators and their mounting, but they also suggest the optimal course in this ongoing research. They suggest a development of diamond radiators that maintain their rigidity through partial surface thinning. The central areas of the wafer surface may be thinned for CB in an electron beam while the edges may be left think to offer support. The laser-ablation techniques described above will be pursued to enable this sort of wafer-shaping.

This result also points to a simplified characterization process in the course of radiator development. Using visible light optics, either through the Zygo optical profiling or through three-wave Michelson interferometry discussed above, it is possible to map the surface shape and deduce the relative changes in wafer curvature. This provides an indirect estimation of the changes in the whole-crystal mosaic spread, allowing a convenient, bench-top estimation of whole-crystal mosaic spread during the process of diamond machining and mounting.

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