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Optical measurement of thermal deformation of multilayer optics under synchrotron radiation

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Abstract

An *in situ* optical technique to visualize surface distortions of the first monochromator crystal under synchrotron beam heat loading has been developed and applied to measure surface profiles of multilayer optics under white wiggler beam at the CHESS A2 beamline. Two identical multilayer structures deposited on Si and SiC substrates have been tested. Comparison of the reconstructed 3D heatbump profiles showed the surface distortions of the multilayer on SiC a factor of two smaller than the same multilayer on a Si substrate.

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Keywords: Synchrotron radiation; High heat-load optics; Heat bump; Surface profile measurement; Optical metrology

1. Introduction

Deformation of the first monochromator crystal under the heat load of a synchrotron beam is a well-known problem. The high heat load may lead to severe deterioration of beam quality, intensity throughput, and energy resolution. The heat load results in a heatbump—a mechanical distortion of the surface topology of the first optical element. A lot of work has been done over the last two decades to reduce this effect by developing contact or internally cooled schemes using water or liquid nitrogen as coolants. Most of the work to study heat load effects is based on the X-ray data, i.e. on measuring the broadening of the X-ray rocking curve as a result of the deformation of the crystal.

Direct measurement of a surface profile of a beamline mirror under high heat load was demonstrated by Takacs et al. [1,2] using a long-trace profiler (LTP). LTP is routinely used to evaluate surface flatness of beam line mirrors with micro-radian accuracy. The LTP is based on using a laser beam reflected from the mirror surface and a mechanical translation stage to probe surface distortions along the length of the mirror. Although the LPT provides excellent accuracy in measuring slope-errors, it provides information only along a line and the method would be hard to implement in confined spaces such as a monochromator. There are examples that demonstrate optical measurement of surface shapes and distortions in 3D. Saeed et al. [3] analyzed images captured with a CCD camera of laser beams reflected from the surface of a weld-pool to recover the shape of the surface. The Shack–Hartmann camera arrangement has been widely used to measure light wave-front surfaces and to reconstruct the surface shape [4]. The technique has found wide application in optometry to measure the aberration of the human eye. The disadvantage of this technique is the limitation on the area of measurement by the size of the CCD chip.

In our previous work [5] we demonstrated a new optical method to map the 3D distortion of a silicon crystal. We have shown how heatbump surfaces can be reconstructed and slope error can be measured using a relatively simple optical arrangement. In this work we present our results on measurements of heatbumps arising on WB_4C multilayer structures deposited on silicon and silicon carbide substrates.

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2. Technique

The schematic representation of the technique is shown in the top part of Fig. 1. The method of heatbump measurement is similar to the method used to recover the wave front (the Shack–Hartmann method). An array of light dots is created by a flat light source with a metal mask placed in front of it. The metal mask has an array of evenly spaced holes producing the light dot array. The light from the dot array is reflected by the crystal surface and captured by the CCD camera. In our experiment the holes in the mask were 300 μm in diameter and evenly spaced 1.5 mm apart over a $100 \times 100\,\mathrm{mm}^2$ area. This light source was mounted inside the vacuum monochromator box on the stage of the second crystal. The CCD camera was placed outside the monochromator to view the image of the light dot array reflected by the multilayer surface. The image frames from the camera were captured and analyzed with a program *Centroid* [6]. This program calculates the centroid position of each light dot on the image. As the reflecting surface becomes distorted due to the heat load, the position of the light dots in the image shift. There is a simple relationship between the change in the position $\Delta\vec{r}$ of the centroids in pixels and the change in slope $\Delta\vec{\Theta}$ of the reflecting surface:

$$\Delta\vec{\Theta} = \frac{\Delta\vec{r}}{ML}$$

where M is the demagnification factor of the camera optics and L is the total optical path length. For each light dot in

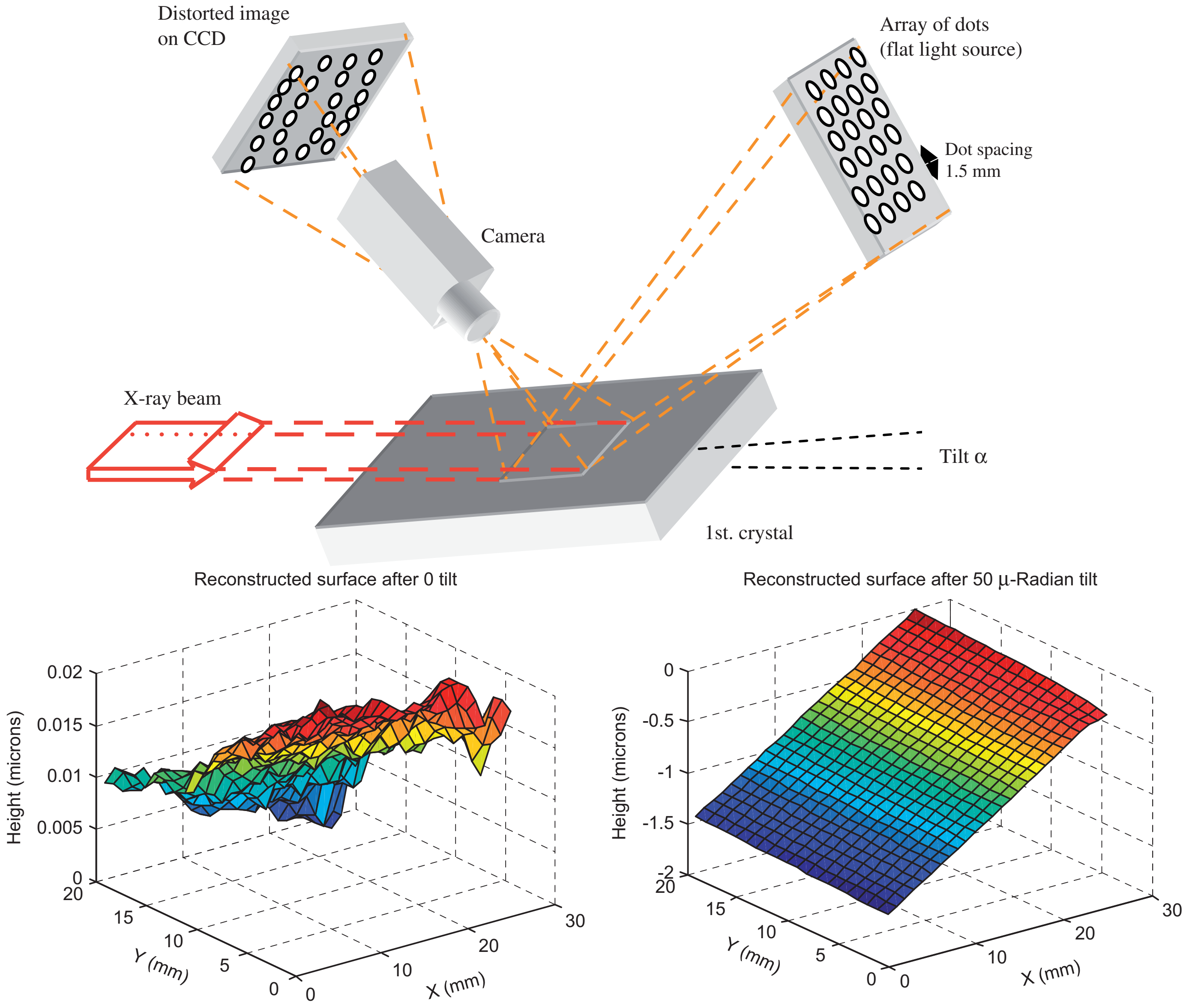

Fig. 1. Top: schematic of the heatbump measurment geometry. The array of light dots is reflected from the mirror surface of the first crystal and captured through the viewport by the CCD camera mounted outside the monochromator box. Bottom: reconstructed surfaces before and after the first crystal was tilted by 50 μm. The titled surface demonstrates the sensitivity of the technique and allows for a precise calibration.

the image there is a corresponding coordinate point on the reflecting surface: the point where the reflection for that light dot takes place. Therefore, by recording $\Delta r_{i,j}$ for each point we obtain the surface gradient map $\Delta\Theta_{i,j}$. In order to determine the values of the gradient map one can use the above equation provided that M and L values are known. In practice, since the first crystal is mounted on a precise goniometer, a simple calibration procedure to determine the relationship between $\Delta\vec{r}$ and $\Delta\vec{\Theta}$ can be used by rotating the crystal by a certain angle and recording the resulting change in the centroid positions. The lower part of Fig. 1 shows the reconstructed surfaces before and after a 50 μrad tilt of the crystal.

Surface reconstruction from gradient maps is a well-studied problem of a "shape-from-shade" [7]. Ideally, the surface can be obtained by simple integration of the gradient field and the resulting surface should be independent of the integration path. In the real experiment, however, the integrability requirement ($\mathrm{curl}(\vec{\Theta}) = 0$) is rarely satisfied due to experimental errors in measuring the gradient field. As we have shown in greater details in Ref. [5], a method minimizing least-square error in the gradient field in the presence of Gaussian noise results in three to four times less error in the reconstructed surface than a linear integration procedure. The method involves the numerical solution of the Poisson equation. The gradient field matrices were calculated and saved by the Centroid program. To reduce experimental errors, the gradient field data were used that averaged over 20 frames after removal of "zingers" (extreme singular pixel data due to scattered X-rays) by median filtering of the images. The reconstruction of the crystal surface has been performed using a Matlab computer program.

3. Experimental results

Heat load response from two multilayers and silicon single crystal have been studied. Both multilayers have the same coating of 300 bilayers of WB_4C with the period of 15 Å deposited on Si and CVD SiC mirror polished (wave precision) substrates. Deposition on both substrates was performed by Osmic, Inc. simultaneously, within the same technological process. X-ray characterization revealed almost identical results for both multilayers' rocking curves with the maximum reflectivity of about 50% and energy bandwidth of 0.5% [8]. The heat load measurements were performed at the CHESS A2 beamline receiving beam from the 49 pole wiggler producing a total power of 6.6 kW. The normal power density at the entrance of the monochromator was ~22 W/mm^2. The incident angle of the beam was fixed at 3°. The footprint of the beam on the crystal was set by the upstream slit both in vertical and horizontal directions. The dimensions of the multilayers were 75 mm × 25 mm × 5 mm thick and the dimensions of the Si single crystal were 75 mm × 50 mm × 10 mm thick.

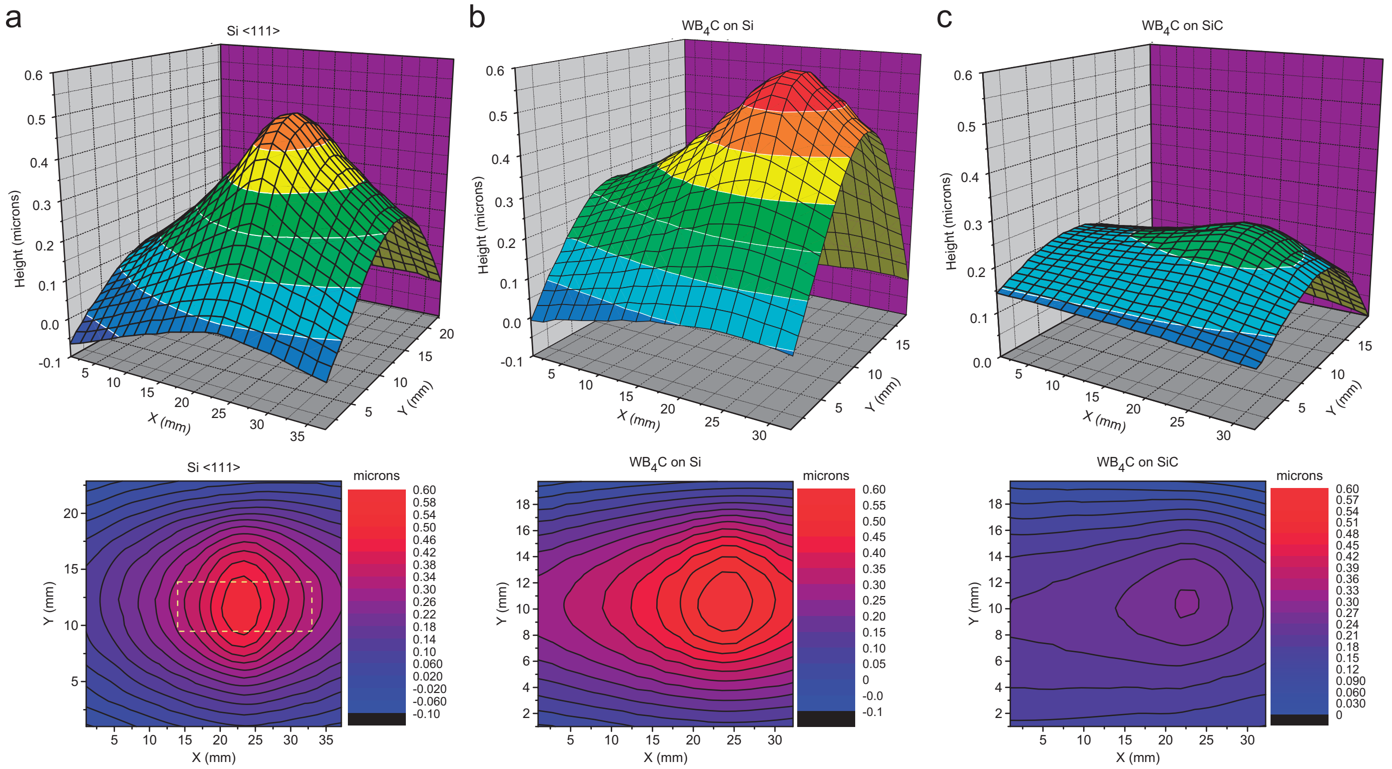

Fig. 2. Reconstructed surfaces of the heat bump produced by the white wiggler beam in the Si crystal (a) and the WB_4C multilayer on Si (b) and SiC (c) subtrates. The incident angle was fixed at 3°. The slit size was 4 mm wide and 1 mm tall. The contour plots are shown below. The dashed-line box shows the beam footprint.

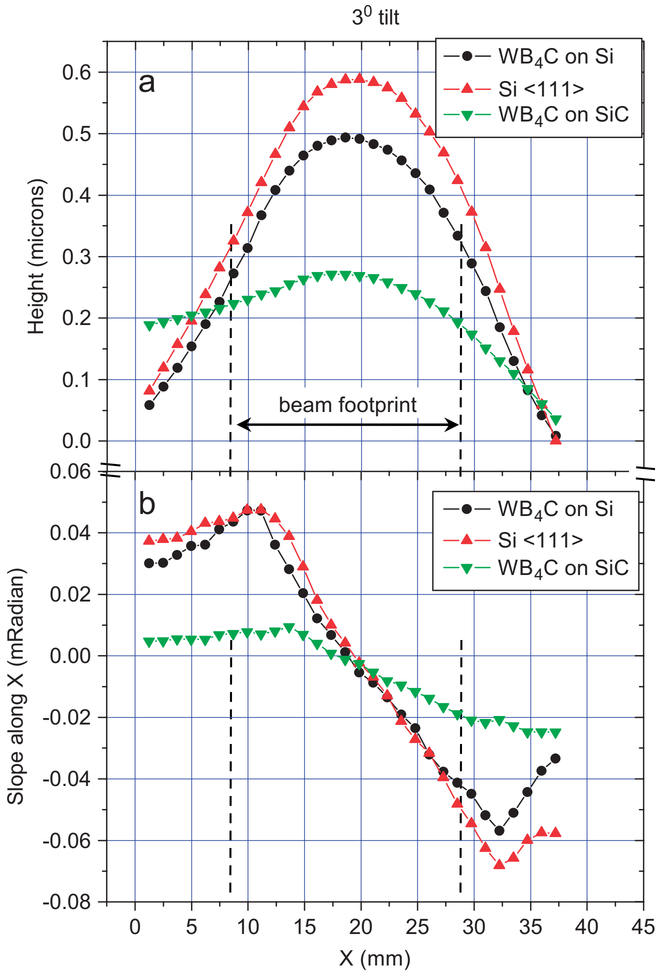

Fig. 3. Comparison of the heatbump profiles (a) and the slope errors (b) for the Si crystal, WB_4C multilayer on Si and SiC substrates as measured along the "crest" of the heatbumps.

The vertical beam size was fixed at 1 mm and the horizontal size varied from 1 to 10 mm. The vertical slit determined the footprint of the beam on the crystal of 19 mm. A $30 \times 20\,mm^2$ area of the crystal defined by the field of view of the optical system was mapped. The distance between the nodes of the gradient field was ~1.1 mm determined by the crystal to light source distance and the light dot density.

In Fig. 2, the reconstructed heat bump surface is shown for the Si crystal (a) and the multilayers on the Si (b) and the SiC (c) substrates. The X-ray beam's direction was parallel to the *X*-axes of the 3D plot. The plots below in Fig. 2 show the contour plots of the surfaces. It is evident from these results that under identical experimental conditions the heat bump for SiC substrate is significantly less than for Si substrate. Obviously, the difference can be explained by a superior heat conductivity of the SiC relative to the single crystal silicon. In Fig. 3, we compare the heatbump profiles (a) and the slope errors (b) measured along the "crest" of the surfaces for the two substrate materials. For the multilayer structures, the heat bump height for the silicon substrate is about 2.2–2.5 times larger than the heatbump measured for silicon carbide. This ratio is in satisfactory agreement with the ratio of heat conductivity of SiC vs. Si.

4. Conclusion

We have developed a new method to measure heat bump surfaces arising on the first monochromator crystal under high power X-ray radiation. The method uses stationary optical arrangements to determine the 3D surface of the distorted crystal. We have applied this technique to study the effect of high heat load on multilayers on silicon and silicon carbide substrates. It is evident from our study that silicon carbide substrate, due to its superior thermal properties, performs better, resulting in a factor of two lower heat bump than for the same multilayer deposited on single crystal silicon.

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