Microbeam X-ray Measurement of Strain and Anticlastic Bending in Silicon under Large Deflection Conditions

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Introduction

Strain and strain gradients are of both fundamental and technological interest in cylindrically bent materials for understanding the elastic and plastic deformation associated with sagittal focusing x-ray monochromators, crumpling of sheets, buckling of cylindrical structures, and the fabrication and performance of microelectro-mechanical structures (MEMSs).

Methods and Materials

We have used white and monochromatic x-ray microbeams at the APS to measure anticlastic bending and make micrometer-resolution depth-dependent measurements of the surface-normal strain and strain gradients in cylindrically bent Si. Differential-aperture x-ray microscopy (DAXM) [1] has been used in a monochromatic mode to measure the surface-normal strain and anticlastic bending in a 25-μm-thick (t) by 8.7-mm-wide (w) Si plate bent into the shape of an arch with a radius of curvature at the apex of R = 3.06 mm [2]. This small bend radius corresponds to the large deflection regime with a Searle parameter (w^2/Rt) of 1009 compared to Searle parameters of <10 for small deflection bends that can be treated analytically.

Results

White-beam measurements of the local surface bending (direct and anticlastic) showed that the large deflection conditions reduced the anticlastic bending at the edges of the Si by a factor of ~5 from that calculated for small deflection conditions. The results at the center of the sample indicated significant anticlastic bending, whereas small deflection theory predicts no bending at the center of the sample for these conditions.

Micrometer-resolution depth-dependent measurements of the surface-normal lattice strain introduced by the 3-mm radius bending were performed by making 2-D scans of the monochromator energy vs. the DAXM wire profiler position [1]. By collecting the (008) Bragg intensity distribution on a charge-coupled device (CCD) detector during the 2-D scan, the local lattice parameter as a function of depth was determined by the DAXM analysis. The inset in Fig. 1(a) shows the (008) Bragg intensity for such a 2-D scan in which the Bragg energy varies with depth as a result of the bend-induced strain

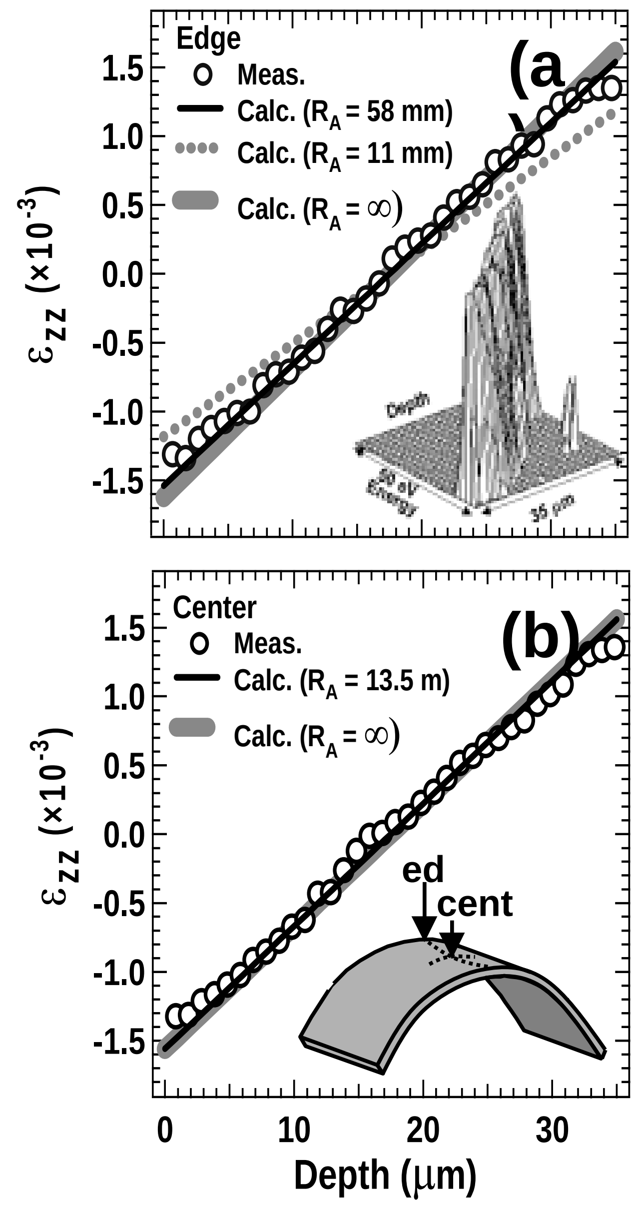

FIG. 1. Depth dependent surface-normal strain measured along the line of the 45° x-ray microbeam penetration direction into <001> oriented Si with <110> oriented edges. Measurements and calculations at 20 μm from the sample edge (a) and at the center of the sample (b).

gradient. The open circles in Figs. 1(a) and 1(b) denote the surface-normal strain relative to the lattice parameter of Si, and the broad solid lines correspond to the strain expected for no anticlastic bending. The thin solid lines represent the strain gradient calculated in the thin-plate approximation, including the measured anticlastic bending. The dotted line illustrates the strain predicted for R = 3.06 mm by using expressions for the small deflection limit [3]. Within the ~10^{-4} estimated uncertainties in the measurements, the results are in good agreement with the calculations when the measured anticlastic bending is included.

Discussion

These results demonstrate that absolute lattice spacing measurements can be made by using the DAXM technique in connection with monochromatic microbeams. Such a capability is needed [1] to obtain the full strain tensor in addition to the deviatoric strain tensor obtained by using polychromatic Laue diffraction measurements. This technique can be applied to a wide range of strained-material systems.

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