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Measurement of Dislocation Density in SiC Wafers Using Production XRT

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Abstract. X-ray topography (XRT) presents itself as an attractive non-destructive method to replace industry-standard destructive KOH etching used to measure dislocation density. However, a production-line-compatible XRT has to employ a low scan speed in order to work well with automated image analysis, which makes it impractical for a high-volume manufacturing to scan an entire wafer. We introduce the “radial band” approach to sampling the entire wafer’s area with a single-pass 16 mm tall scan band. Such a band spans the entire range of radii and thus captures the typically strong radial dependence of dislocation density over the entire range, while mostly ignoring the typically weak angular dependence of dislocation density and averaging the inevitable noise over the 16 mm band height. The XRT scan time savings for this approach are roughly 15-fold and 20-fold for 150mm and 200mm wafers respectively.

Introduction

Single crystal wafers of 4H SiC are the top choice for power electronic device substrates due to their excellent thermal and electrical properties. One of the most consequential defects limiting device performance and longevity are dislocations. In particular, threading edge dislocations (TEDs) and threading screw dislocations (TSDs) can both reduce minority carrier diffusion lengths over a range of dopant concentrations [1]. TSDs have been found to reduce breakdown voltage in p+ n diodes [2]. TEDs can also convert to basal plane dislocations (BPDs) [3] or enhance their formation [4], which can lead to bipolar degradation via the formation of stacking faults [5].

The KOH etch pit counting method [6] has been traditionally used in the industry as a destructive and hazardous technique to measure TED, TSD, and BPD densities. X-ray topography (XRT) has been long known as an imaging method that can reveal dislocations non-destructively due to its exceptionally high sensitivity to strain in a crystal. Recently, a production-line-compatible XRT instrument has become commercially available [7]. The purpose of this study is to explore the promise of a production-line-compatible XRT as a non-destructive, low-hazard (with proper X-ray containment) alternative to KOH etch pit method of measuring dislocation densities in production.

Experimental

Single crystal 4H n-type SiC boules were grown by a seeded physical vapor transport method. The crystals were then fabricated into 150mm and 200mm wafers via grinding, slicing, and polishing. The wafers were scanned in a Rigaku XRTmicron instrument without a monochromator using Cu $K_{\alpha 1}$ radiation in reflection mode, using $\boldsymbol{g}$ = $[11\overline{2}8]$ and $\boldsymbol{g}$ = $[0008]$ diffraction vectors. The former reflection reveals both threading and basal plane dislocations. The molybdenum target available in this tool, which enables transmission mode XRT, was not used, since high-BPD-density regions would produce highly overlapping images of BPDs located throughout the thickness of the wafer and thus degrade the accuracy of image analysis.

Results and Discussion

Due to a relatively low flux of X-rays available in a production-line-compatible instrument, in order to achieve needed image quality (e.g. Fig. 1 (a)) to resolve dislocations in XRT images compared to a synchrotron source which has orders of magnitude stronger intensity, the scan speed must be on the order of a few mm/min. With 1.6 cm being the height of a single-pass scanned image (band), which is determined by the XRT detector size, imaging an entire wafer requires scanning and then stitching multiple horizontal band images. This takes many hours, which is too long for high-volume manufacturing.

(a) (b) (c)

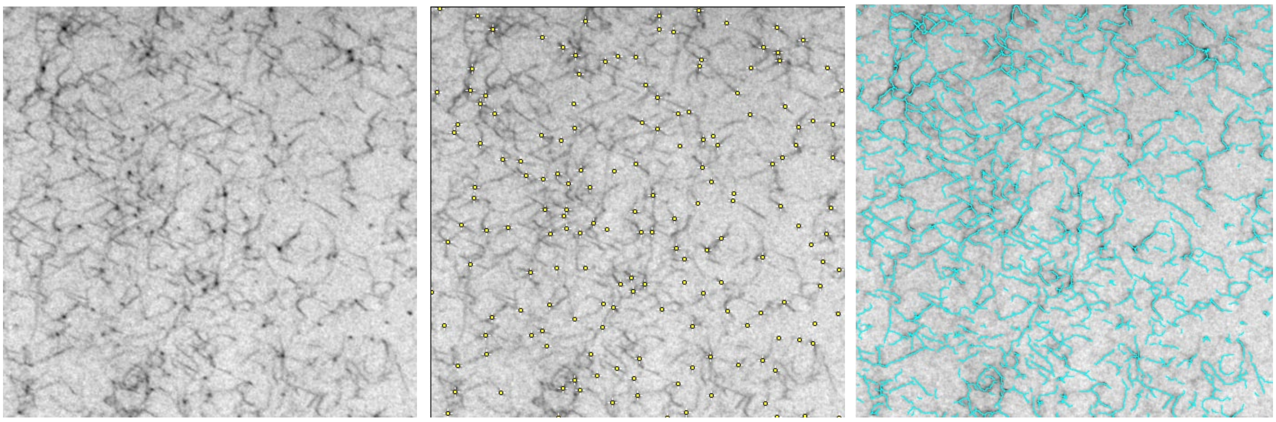

Figure 1. (a) 5×5 mm XRT image and overlaid automated image analysis results: (b) found TED/TSD spots labeled with ○ markers, (c) found BPD curvilinear features.

Fortunately, our extensive KOH analysis results (Fig. 2) and data from several whole-wafer XRT scans show that in polar coordinates the radial dependence of dislocation density is much stronger than the angular one, i.e. the distribution of dislocation density over a wafer is well-approximated by a surface that is a body of revolution. This high degree of rotational symmetry means that XRT scanning a single radial band is an effective and efficient sampling strategy, as is illustrated in Fig. 3. In order to cover the whole range of radii we only need to scan ≈1/15 of a 150 mm wafer's area. For 200 mm wafers, the 1.6 cm tall radial band, e.g. Fig. 4, is even more time-efficient, since it occupies a further reduced fraction of the wafer's area: 1.6×10 = 16 cm^2, which is only ≈5% of $\pi(10\ cm)^2$.

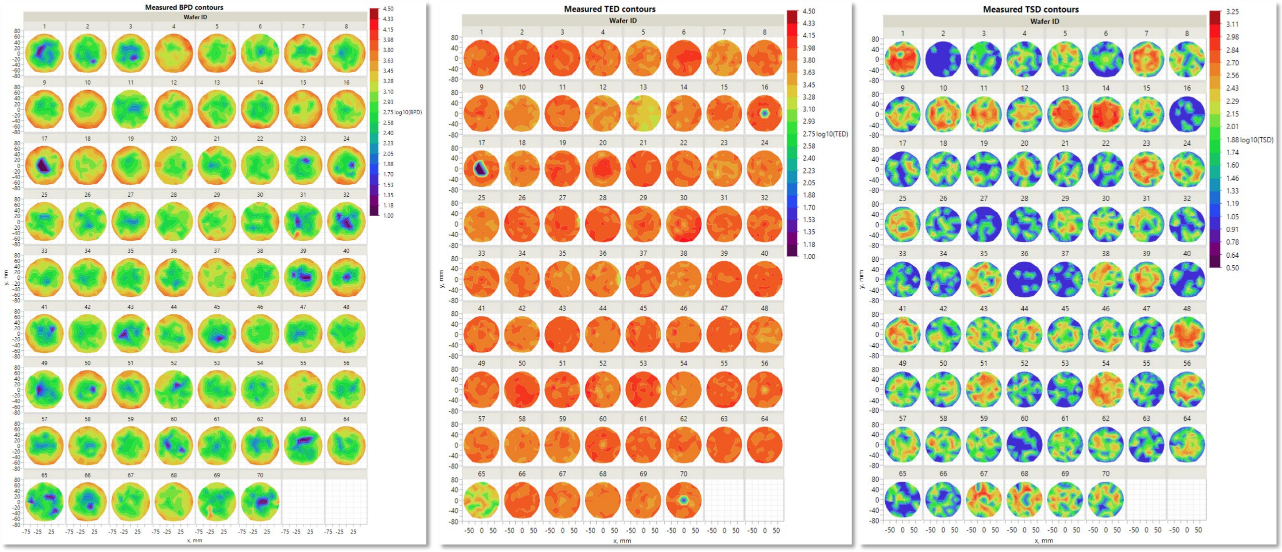

Figure 2a. Contour maps in logarithmic scale of KOH etch pit density [cm^{-2}] data for 70 randomly selected wafers (one per boule) illustrating strong radial dependence and weak angular dependence of spatial distribution of dislocation densities in polar coordinates for all three dislocation types of interest (from left: BPD, TED, and TSD).

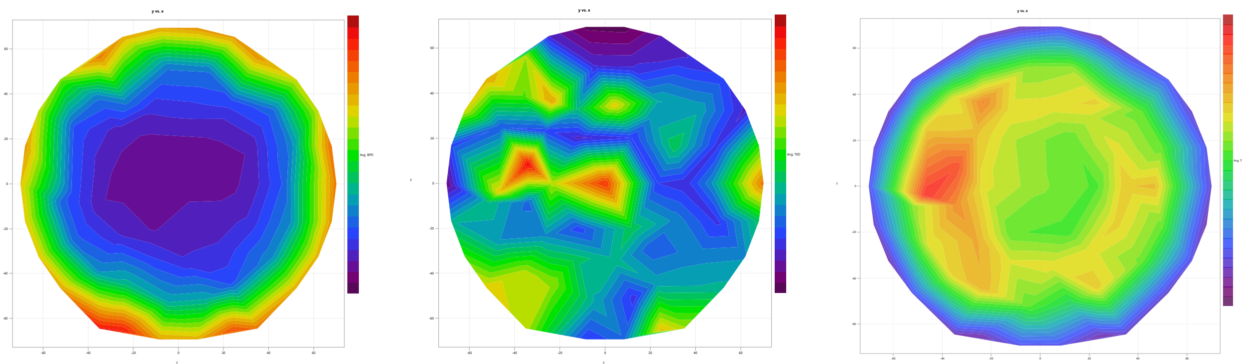

Figure 2b. Contour maps of KOH etch pit density [cm^{-2}] obtained by averaging maps for 70 wafers shown in Fig. 2a. From left: BPD, TED, and TSD. Distance units: mm.

Since threading dislocations appear as spots (TSD typically have higher intensity due to a larger associated lattice strain than TEDs), whereas BPDs appear as curvilinear features (often overlapping or forming junctions), we developed separate algorithms for automated measurement of (1) TSD & TED areal spot density [cm^{-2}] and (2) total BPD length per unit image area [cm/cm^2]. The latter value is divided by the effective imaging depth to arrive at BPD density [cm^{-2}] shown in Fig. 3. The effective imaging depth depends on the X-ray energy, diffraction vector, and the sensitivity of the BPD detection algorithm. It can be empirically found by correlation with the results of other dislocation density measurement techniques and should roughly match the X-ray penetration depth.

Fig. 3(b) can be used to estimate percentage, i.e. probability, of passing 2x2 mm devices as a function of radius, i.e. the distance from the wafer center. For example, if a specification limit is represented by one of the horizontal gridlines, say 2000 cm^{-2}, the probability of a passing device starts off at nearly zero at low radius values (where all red markers are above the limit), then increases dramatically toward the middle of the radial band (where most of the red markers are below the limit), and then drops off to nearly zero at the periphery.

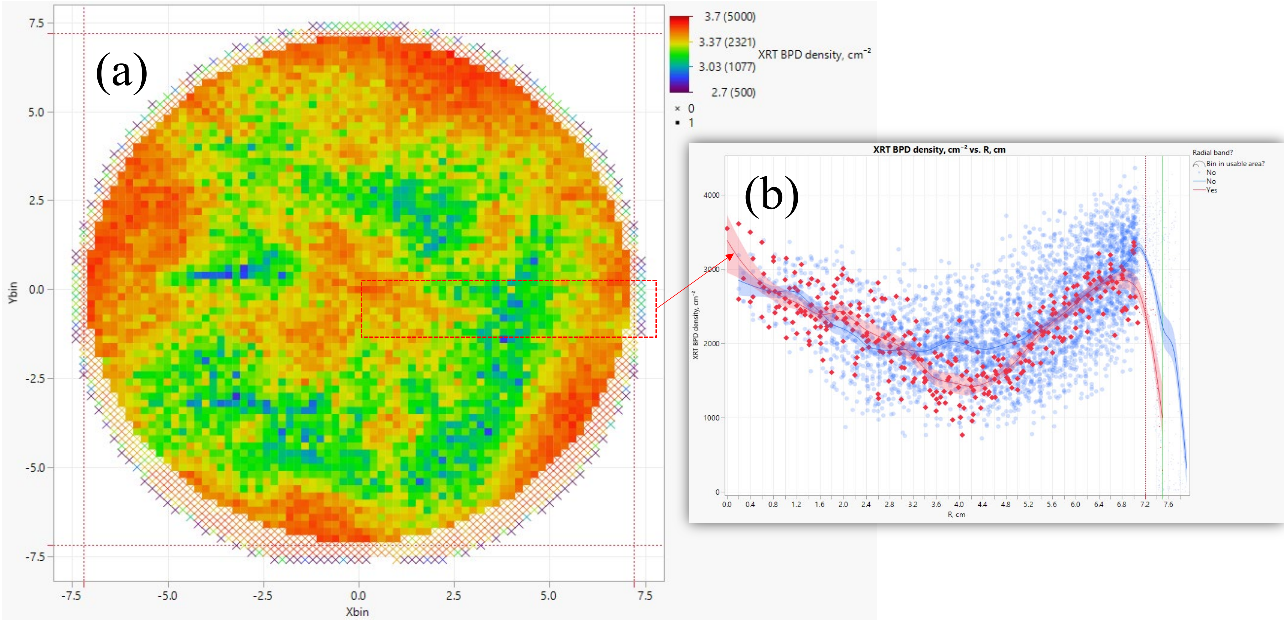

Figure 3. XRT automated image analysis results for BPD density in a randomly selected wafer: (a) whole-wafer heat map (2×2 mm tiles) with overlaid 16 mm tall single radial band scan area ⬚; (b) radial profiles for the whole-wafer scan (blue) and for the radial band scan area only (red). Note how well the red curve approximates the blue one, while it costs at least an order of magnitude less in terms of the scan time. X, Y, and R (distance from wafer center) axes have units of cm.

The endeavour of replacement of a relatively simple counting and classifying method for pits on a KOH wafer's surface with an image analysis of a grayscale XRT image, which has a vanishing contrast of features located below the top surface of a wafer as the depth of the features increases, is not without its challenges. First, the total detected BPD length in XRT image poorly correlates with KOH etch pit results. This is most likely due to an orientation-dependent proportionality coefficient between BPD length within the imaged depth and areal density of intersections of BPDs with any plane parallel to wafer's surface, i.e. BPD etch pit density. We are currently exploring an orientation-sensitive approach to conversion of XRT-measured BPD length to predicted BPD etch pit density. Second, separation of TSD and TED is a challenge for a $\boldsymbol{g}$ = [11$\bar{2}$8] reflection XRT image due to significant overlap of the distributions of intensities and geometric atributes of TSD and TED spots there. Theoretically, in a $\boldsymbol{g}$ = [0008] reflection image (e.g. bottom XRT image in Fig. 4) only TSDs should produce a contrast, but surface relaxation around TED terminations may still produce dark spots there and thus complicate the analysis. Adding a $\boldsymbol{g}$ = [0008] scan may be needed to isolate TSDs and thus calculate TED density as the difference between spot densities of $\boldsymbol{g}$ = [11$\bar{2}$8] and $\boldsymbol{g}$ = [0008] reflection images. This is one of the directions of our ongoing work.

Figure 4. 1.6-cm-tall XRT radial band scans of the same area of a 200mm wafer using two shown reflections. The wafer‘s center is at the center of the left edge of each image. The top image includes the wafer‘s edge. Orientation of the $[11\bar{2}0]$ direction: →.

Summary

XRT Cu $K_{\alpha 1}$ radial band scans are an effective and efficient sampling strategy compatible with high-volume manufacturing, allowing <10% inaccuracy at ≈15× and ≈20× shorter scan time for 150 mm and 200 mm wafers respectively. BPD (curvilinear features) and TD (spots) detection calls for different image analysis algorithms. We are working on a better prediction of BPD etch pit density using an orientation-sensitive data analysis approach and exploring the potential benefits of adding ***g*** = [0008] scan to isolate TSDs and thus measure densities of all three dislocation types of interest.

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