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Whole-Wafer Mapping of Dislocations in 4H-SiC Epitaxy

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Abstract. A non-destructive technique to image the dislocations and other extended defects in SiC epitaxial layers has been developed. Basal plane dislocations (BPDs) and threading dislocations (TDs) are imaged. Photoluminescence from the dislocations is excited with the 364 and/or 351 nm lines of an argon ion laser and near-infrared light is collected. A computer controlled probe station takes multiple images and the mm-sized images are stitched together to form whole-wafer maps. The technique is applied to a set of four n^+ wafers from the same boule with 50 um n^- epitaxial layers. The epitaxy was grown with Cree's low-BPD process. BPDs form as either single, isolated dislocations or as clusters encircling micropipes. The concentration of TDs is on the order 10^4/cm2 and the local concentration varies more than an order of magnitude. The advantages of mapping dislocations by UV-PL imaging compared to other techniques are discussed.

Introduction

Power devices fabricated with SiC are in a transition period. While it has long been known that many of the physical properties of SiC make it an ideal material for power devices, it is only recently that its potential has begun to be realized. Schottky diodes are now commercially available and other power devices are being developed. A significant factor in this progress has been the reduction of extended defects resulting from improved bulk and epitaxial growth [1]. Wafers free of micropipes have been grown [2]. The density of basal plane dislocations, which are responsible for the V_f drift in PiN diodes, has been reduced by more than an order of magnitude [3]. Further improvements will rely heavily on the ability to rapidly and accurately measure and characterize the extended defects.

Electro- and photoluminescence (EL and PL) imaging techniques have been shown to be useful in examining dislocations and other extended defects in epitaxial layers. Using EL imaging of PiN diodes with gridded metal contacts, the growth of BPDs during forward-biased diode operation has been observed [4,5]. Photoluminescence imaging has also been employed to image dislocations [6-9]. As densities of defects such as BPDs decrease, larger areas must be examined to obtain meaningful results. In this paper, we present and discuss a UV-PL technique for mapping all of the basal and threading dislocations in a thick epitaxial layer of a 3 inch SiC wafer.

The UV-PL mapping has several advantages compared to other commonly used methods for examining dislocations. It is both non-contact and non-destructive making it possible to screen wafers before fabrication. The setup is simpler than that for x-ray topography and only dislocations in the epitaxial layer are imaged. In the development of low-BPD epi, this technique could replace the expensive and time consuming task of fabricating test PiN diodes for evaluating the epitaxial growth.

Experimental Details

The dislocations in 50 μm n^- - 3×10^{14} cm^{-3} - epitaxial layers on 3 inch n^+ wafers have been mapped. The wafers used were the 4H polytype and 8° off axis. They included an n^+ epitaxial buffer layer on the substrate and the Cree low-BPD process [1]. This combination is typical for the drift region of a PiN diode with 5 kV blocking. Four adjacent wafers from the same boule were mapped. Each had the same epitaxial growth. While the wafers used in this work did not have epitaxially grown p^+ layers on top of the n^- layer, we have done the same dislocation mapping of wafers including the p^+ epitaxy and obtained similar results.

The PL images were collected in a computer controlled probe station. The UV excitation above the 4H bandgap was from an argon ion laser. Both the 364 nm and 351 nm lines were used and the resulting images are comparable. The penetration depth at 364 nm is 120 µm and at 351 is 35 µm [10]. Either is sufficient to image dislocations through the full thickness of the 50 µm thick epitaxial layer. Individual images ~1 mm^2 with micron scale resolution were collected with a liquid nitrogen cooled CCD. Under computer control, a sequence of overlapping images covering the whole wafer was collected. The total collection time was typically 10-20 hr. The threading and basal plane dislocations were imaged using the PL light in the 800 to 1000 nm range. This range was found to yield the best image contrast and to provide the best discrimination between the dislocation PL and the background from the substrate. Dislocations were only observed from the lightly doped n^- epitaxial layer. The final full-wafer image was assembled after image processing to remove laser beam non-uniformities and to align the individual images.

Results and Discussion

An example of a full-wafer map is shown in Fig. 1(a). Except as noted, the other images are magnified sections of Fig. 1(a). While individual dislocations are much too small to see, there are clusters of dislocations near the wafer edge that are brighter than the rest of the wafer. Fig. 1(b) is a magnified view of the cluster inside the rectangle near the edge.

The BPDs in the epitaxial layer appear in three patterns. The first are in mass clusters such as in Fig. 1(b). The second are smaller, roughly circular clusters, which are also seen in Fig. 1(b). The inset in Fig. 1(b) is a magnified view of two of the small clusters. The third way that BPDs appear is as individual, isolated dislocations, such as shown in Fig. 2. Only in the third case is it possible to count individual BPDs. The first two are BPDs formed by the stress field around a micropipe. Fig. 1(c) is a micropipe map from another wafer in the same boule obtained from KOH etching. The patterns are nearly identical and the clustering behavior of the BPDs is dictated by the closeness of the micropipes. Where the micropipes are closely grouped, the BPDs are tangled together resulting in a mass cluster. When the distance between micropipes is larger, distinct circular clusters of BPDs are observed around each micropipe. The same pattern of multiple BPDs encircling micropipes has been observed in SiC substrates by x-ray topography [11].

Examples of the small circular clusters are labeled 1-5 in Figs. 1(b) and 1(c). The distance between clusters 1 and 2 is 300 µm. At shorter separations and with more grouped micropipes, the clusters merge. The micropipe at the center of cluster 5 in Fig. 1(b) does not appear in the micropipe map. Also note that micropipe 4 is closer to the edge of the wafer in the micropipe map, Fig. 1(c), than in the dislocation map, Fig. 1(b). On the micropipe map, micropipe 5 is outside the wafer. Further evidence for BPD clusters encircling each micropipe is provided by comparing Figs. 1(b) and 1(d). The latter is a dislocation map at the same location from a different wafer in the same boule. The overall patterns from the two wafers are the same, although as the micropipe positions vary through the boule, the details of the dislocation patterns are slightly altered. For example, micropipe 4 in Fig. 1(b) appears to have split into two micropipes in Fig. 1(d).

Individual BPDs and threading dislocations (TDs) are shown in Fig. 2. This figure is an expanded region of the dislocation map outlined by the small rectangle near the center of Fig. 1(a). Within the field of view, there are 4 BPDs and about 200 TDs. Because the TDs are roughly perpendicular to the wafer surface, they appear as dots. Note that many of the dots are elongated due to the tilting of the TDs away from perpendicular. The concentration of TDs is about 10^4/cm^2 in this figure and varies by more than an order of magnitude in different parts of the wafer. The BPDs appear as a combination of bright straight segments and fainter curved segments in Fig. 2. The entire length of two of the BPDs, (a) and (b), through the n^- epitaxial layer can be seen. There are two arrows for BPDs (a) and (b). The left arrow at each BPD is near the substrate/epi interface and the right arrow is at the epi surface. The portions of the dislocations in the n^+ substrate and probably the n^+ buffer layer are not observed. The offcut angle and the n^- epitaxial thickness determine the left-right distance of BPDs that span the n^- layer. With an offcut angle of 8° towards the left, BPDs propagate 7 µm from left to right for every µm towards the surface. The left to right distances of BPDs (a) and (b) are both 340 µm, which is in close agreement with the 350 µm length expected from a 50 µm thick n^- epitaxial layer.

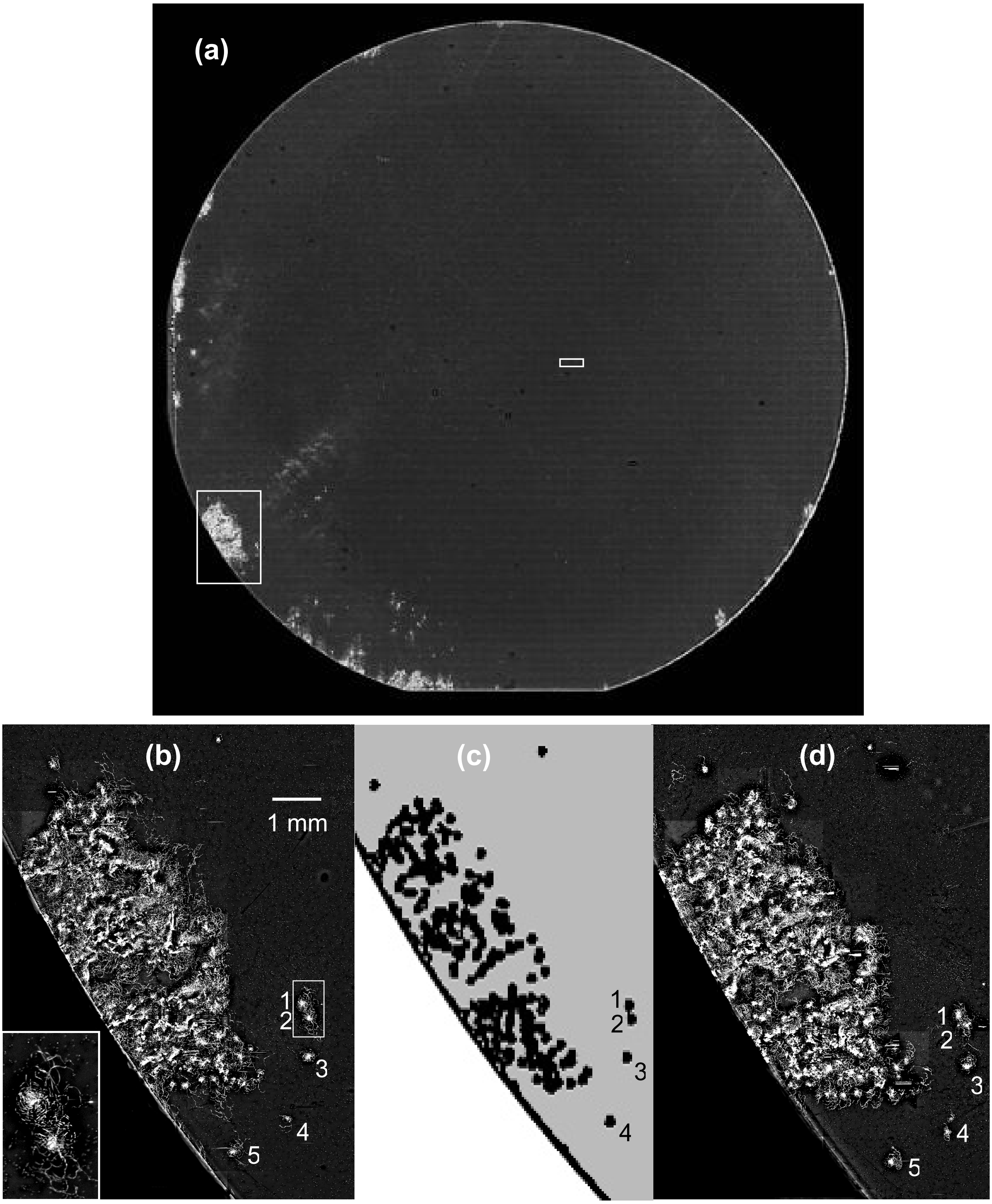

Fig. 1. Comparisons of maps of dislocations in epitaxial layer of a 3 inch 4H-SiC wafers and micropipe map: (a) UV-PL map of the full wafer, (b) 4X view of edge boxed area, (c) µpipe map from another wafer in the same boule, (d) UV-PL map from same region as in (b) from a third wafer in the same boule. Inset in (b) is of 2 µpipes and surrounding BPDs.

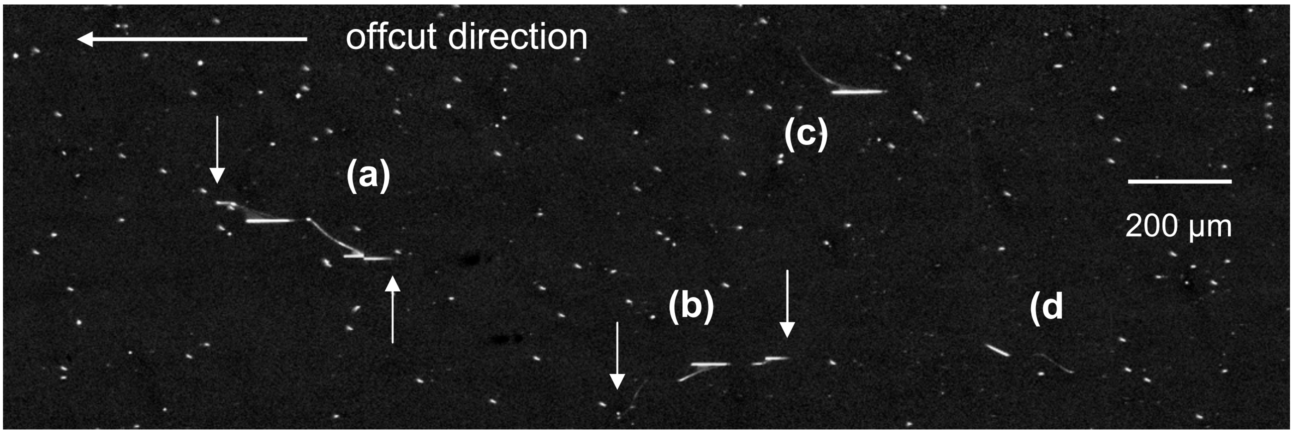

Fig. 2. Magnified view of area inside small rectangle near center of Fig 1(a). This area contains four BPDs labeled (a)-(d). Each dot is a threading dislocation. The total length of BPDs (a) and (b) within the epitaxial layer is observed. The arrow at the left end of the BPD is at the substrate/epi interface and the one at the right is at the epi surface.

Summary

A non-destructive UV-PL technique for imaging and mapping BPDs and TDs in SiC epitaxy over a complete wafer has been demonstrated. In low-BPD epitaxy, the BPDs are either single, isolated dislocations or clusters of BPDs encircling micropipes.

The UV-PL technique has many advantages over alternate methods for mapping dislocations. Unlike KOH etching, it is non-destructive. There is no device fabrication such as is needed for EL imaging of dislocations in PiN diodes. The whole wafer is mapped with micron-scale resolution. This technique could be used for pre-fabrication screening of wafers or as a substitute for test wafer fabrication in the development of low-BPD epitaxial growth processes.

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