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Investigation of Micropipe Defects and Their Strain Field Distortions in SiC Substrates Using X-Ray Topography

Li Sun[1,2,a] Xuejian Xie[1,2,b*], Xiufang Chen[1,2,c*], Xianglong Yang[1,2,d], Yan Peng[1,2,e], Xiaobo Hu[1,2,f*], Xiangang Xu[1,2,g]

[1]State Key Lab of Crystal Materials, Shandong University, Jinan, 250100, PR China

[2]Institute of Novel Semiconductors, Shandong University, Jinan, 250100, PR China

[a]sdusunli@sdu.edu.cn, [b]xiexj@sdu.edu.cn, [c]cxf@sdu.edu.cn, [d]yangxl2016@sdu.edu.cn, [e]pengyan@sdu.edu.cn, [f]xbhu@sdu.edu.cn, [g]xxu@sdu.edu.cn

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Abstract. Micropipe defects in silicon carbide (SiC) materials significantly degrade the performance of SiC materials and their applications in semiconductor devices. In this study, systematic methods were utilized to characterize different micropipes in 4H-SiC. X-ray topography was employed to investigate the morphology of micropipe defects in SiC substrates and quantify their associated lattice distortion fields. Meanwhile, white light interferometry mode microscopy and inner stain were utilized to thoroughly characterize their properties. It was found that micropipes were accompanied with different size and distortion areas in SiC substrate. This work will be served as a refined characterization of micropipes and give guidance for device application for SiC substrate.

Introduction

Silicon carbide (SiC) has shown revolutionary potential in the field of power semiconductor devices due to its excellent properties. Micropipe defects in SiC materials are hollow tubular line defects formed during crystal growth, typically extending along the <0001> crystal growth direction. These defects significantly degrade the performance of SiC materials and their applications in semiconductor devices, leading to detrimental effects such as reduced breakdown voltage, increased leakage current, and diminished carrier mobility. [1-4] Consequently, controlling micropipe defects is critically important during the preparation of large-diameter SiC single crystals.
The influence of micropipe area in SiC crystals on device performance is comprehensive, Large-area micropipes significantly exacerbate device failure risks, particularly in high-voltage, high-temperature, and high-frequency applications. With the gradual optimization of the growth process, the current micropipe density has been greatly reduced, and the characterization of micropipes is facing the requirement of more refinement. Current characterization methods for micropipes primarily rely on various microscopy techniques: polarized transmission microscope reveals stress variations induced by micropipes, while white-light interferometry precisely identifies their hollow core positions.
In this paper, the micropipe was characterized by orthogonal polarizing microscope, white light interference microscope, X-ray topography and inner stress meter. On the premise of accurately obtaining the position of micropipe, the influence of micropipe on the distortion range of crystal was studied synchronously, which will be of great significance to further improve the quality of SiC single crystal.

Materials and Methods

Sample fabrication: The samples were homemade 4H-SiC single crystal with an off-axis of 4°, which were grown by physical vapor transfer method. The growth temperature was set at about 2000°C~2200°C, and nitrogen gas was introduced during the growth process to obtain nitrogen doped boule. The samples all went through chemical mechanical polish (CMP) processing to remove surface scratches and other processing defects.

Characterization: For X ray topography characterization, the images were taken by reflection geometry was performed on the Cu target (λ= 1.54 Å) using diffraction vectors $\vec{g}$=0008, using the 1.2 kW Cu/Mo rotating anode target XRT system provided by Rigaku. White light interference images were taken by microscope fabricated by Sensofar. For inner strain, SV200 wafer stress detector was used by birefringence effect of polarized light.

Results and Discussion

Fig. 1 presented an image of micropipes acquired using an orthogonal polarization microscope by transmission mode. The dark regions corresponded to areas free of micropipes on the substrate surface, while the bright areas arised from alterations in the optical path induced by the presence of micropipes. Fig. 1a and 1b depicted regions containing a single micropipe and double micropipes, respectively. Comparative analysis clearly reveals distinct imaging characteristics between these two configurations. In the single micropipe region, the micropipe exhibits an image with cubic symmetry, consisting of three bright and three dark zones arranged symmetrically around the micropipe center. In contrast, within the double micropipe region, the micropipe images displayed significant distortion due to mutual interaction. This observation indicated the presence of interaction between adjacent micropipes, leading to synchronous modification of the lattice distortion regions associated with their existence.

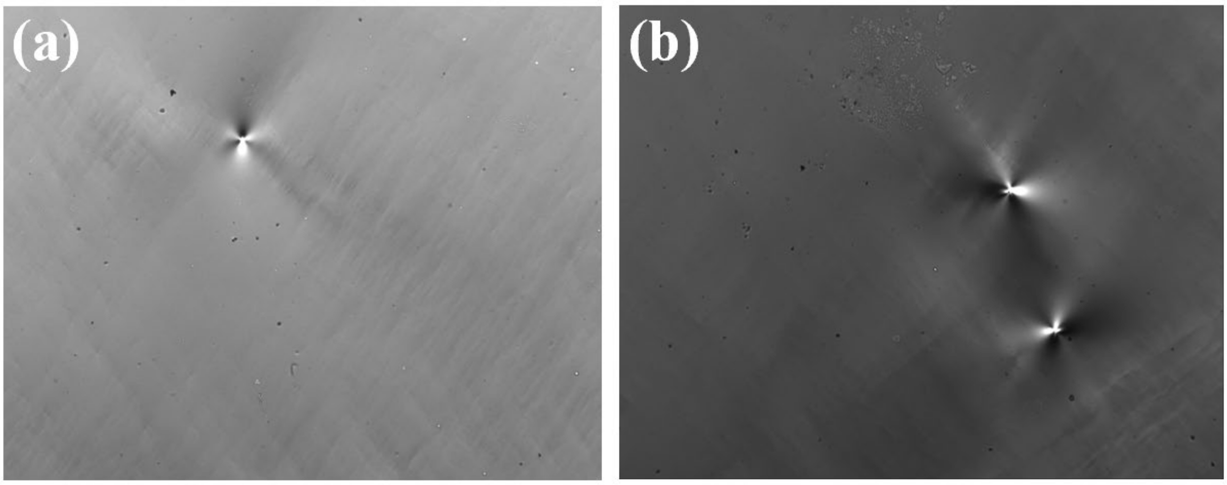

Fig. 1. Comparison single micropipe and double micropipes in polarizing microscope.

X-ray topography (XRT) is an important means to characterize lattice defects, which can effectively characterize the influence range of defects on perfect lattice.[5-6] The Burgers vectors of micropipes (MPs) are expressed as $\vec{b}_{MP}$=±nc(n=3~10), whereas those of threading screw dislocations (TSDs) in SiC substrates are $\vec{b}_{TSD}$=±mc(m=1,2).[7] When identifying MPs in SiC substrate using XRT systems, both MPs and TSDs coexist. The distinction between MPs and TSDs in XRT imaging arised from the inequality $||\vec{b}_{MP}| > |\vec{b}_{TSD}|$. Fig. 2 demonstrated the contrast between MPs and TSDs in SiC substrates under $\vec{g}$ = 0008 diffraction condition. The small black dots were TSD defects, the white hollow and relatively large black dots represented micropipes, and the white area in the middle was the atomic depletion area formed by the presence of micropipes, because it cannot be imaged in XRT. Fig. 2b showed the XRT image of the double micropipe position. Typically, the double micropipe was generally formed by micropipes with different spiral properties. Located at the upper and lower ends, the two MPs interacted and gave rise to an extensive distorted area in the center that cannot be imaged by XRT, corresponding to a region where the 4H-SiC crystal structure was disrupted. Taking dark regions in XRT images as strain-affected areas, single and double micropipe were measured as 0.44 mm² and 1.2 mm², respectively.

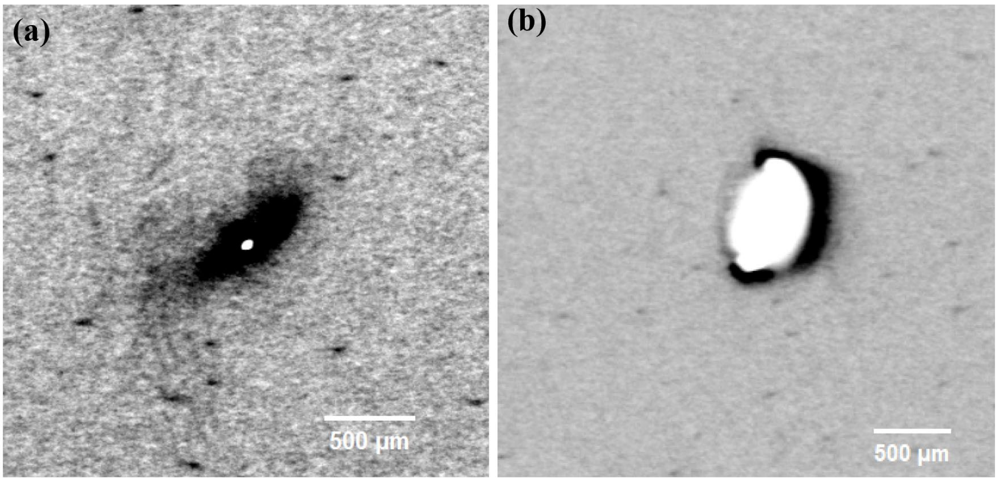

Fig. 2. Comparison single micropipe and double micropipes in XRT.

The white light interference mode of microscope is an effective means for micropipe recognition. The white light interference mode can effectively avoid the influence of the strain factory caused by the orthogonal polarization mode of transmission mode, and more directly reflect the intrinsic characteristics of micropipe. As illustrated in Fig. 3, micropipes exhibited diverse morphologies including elliptical and irregular configurations. By extracting major and minor axis dimensions from these morphological profiles, the corresponding micropipe areas were calculated, with results summarized in Table 1. The measurement range of micropipe dimensions in white light interference mode of microscope predominantly was within 5-10 µm. A synchronous statistical analysis of identical micropipes through XRT revealed that the central white spot areas corresponding to micropipes consistently approximate 10 µm. This comparative analysis demonstrates the feasibility of utilizing XRT as a direct characterization method for quantifying micropipe areas.

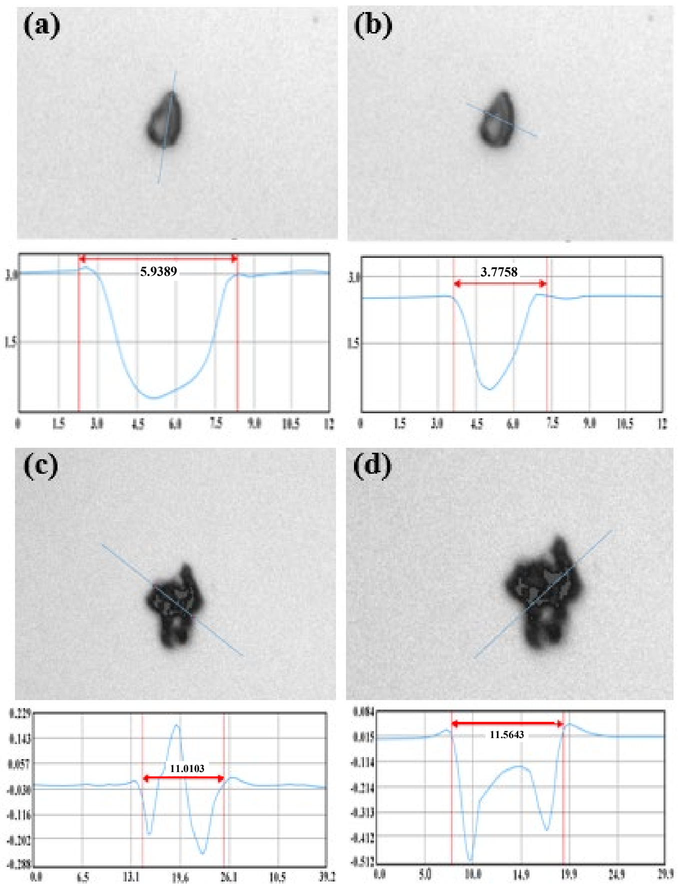

Fig. 3. Micropipe image from White Light Interference Microscope.

Table 1. Comparison of micropipes size between White Light Interference Microscope and XRT.

Length/um		MP-1	MP-2	MP-3
Microscope	Major axes	5.9389	11.0103	4.3960
	Minor axes	3.7758	11.5643	2.6325
XRT	Major axes	18.4937	13.2033	18.2416
	Minor axes	10.6501	12.3507	17.2380

The distribution of micropipes in the same wafer was characterized by XRT and polarizing microscope. Fig.4a showed the XRT imaging of the 8-inch wafer. By adjusting the contrast, the distribution of micropipes in the picture can be clearly seen, as shown in the red box. It should be noted that there was a large bright color area in the lower right corner of the wafer, but according to the micropipe characteristics mentioned above, it can be determined that this position was not a micropipe, but should correspond to the rest of the defects, probably multi type defects. Similarly, in Fig. 4b obtained from transmission microscope , micropipe images appeared at the same position as in Fig. 4a. Comparatively, defects in the lower right corner was recognized as micropipes, which also proved that XRT was the most effective way to identify micropipes.

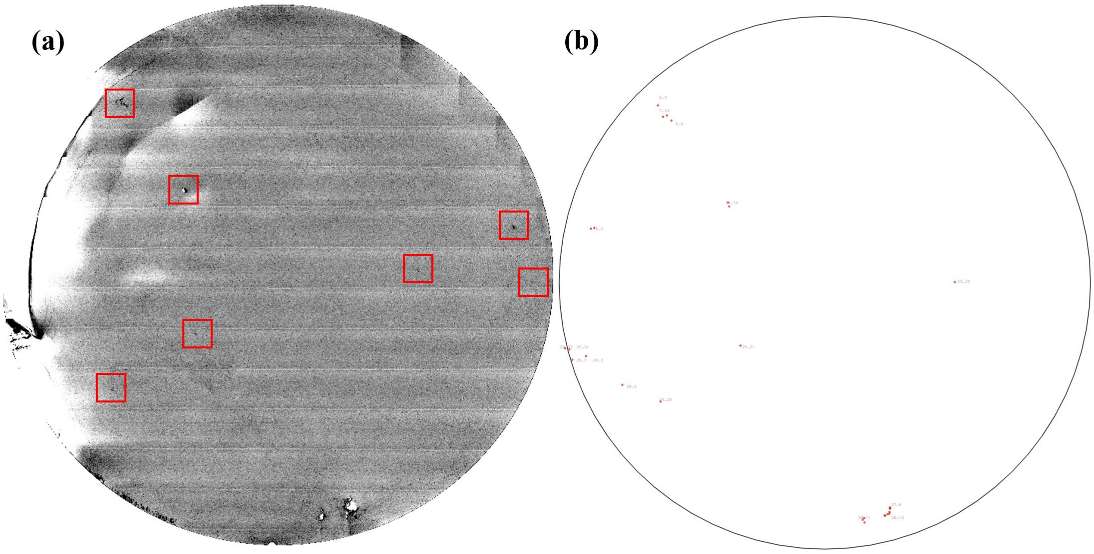

Fig. 4. Micropipe distribution on whole wafer, (a)XRT and (b) transmission microscope.

To investigate the influence of micropipes on the overall stress distribution within the crystal, the wafer stress was mapped using an internal stress meter. Fig. 5a presented the resulting stress map, where the color intensity corresponded to the stress magnitude: darker shades indicate lower stress, while brighter regions signified higher stress. By comparing this stress map with the XRT image in Fig. 4a, it was evident that locations containing micropipes consistently exhibited significantly elevated stress levels.

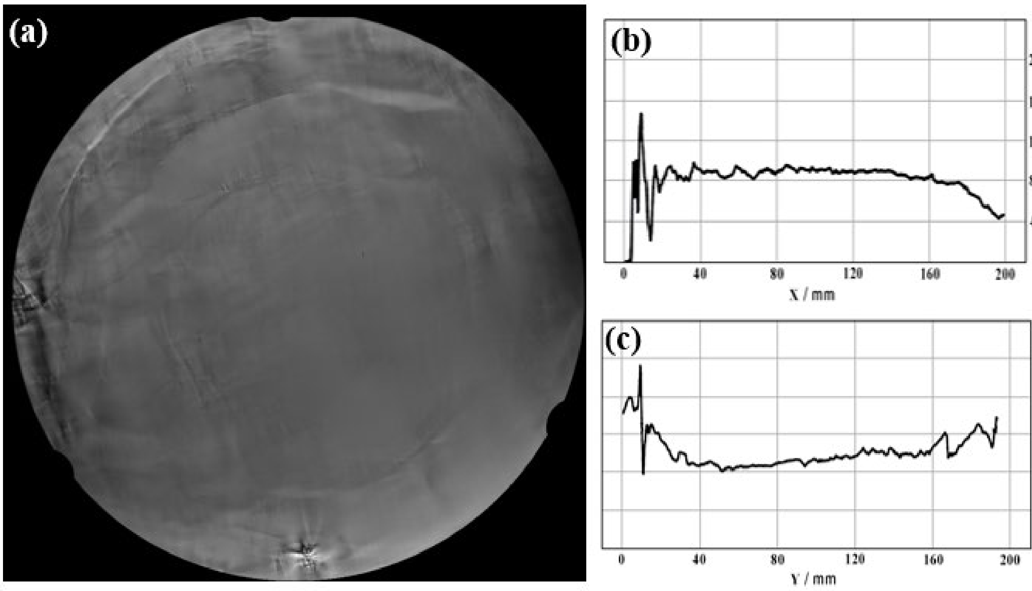

Fig. 5. Inner strain distribution on whole wafer.

Summary

In conclusion, this study presented a systematic investigation of micropipe defects in SiC crystals. By correlating XRT with white light interferometry, we directly revealed the lattice distortion caused by micropipes and demonstrate that the degree of distortion was correlated with the micropipe size. Consequently, the impact of micropipes on the crystal lattice varied significantly with their dimensions. In the characterization of the quality of SiC substrate, the size of micropipes also need to be considered apart from the distribution position of micropipes.

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