学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Microscopy study of correlation between residual elastic strain and defects in He^+ ion irradiated 4H-SiC

(He^+ イオン照射した 4H-SiC の残留弾性歪と欠陥の相互関係に関する顕微学的研究)

Silicon carbide (SiC) has drawn great attention for electronic and optical applications owing to its excellent mechanical, optical and electronic properties, which has also been proposed as structure and cladding materials in nuclear or aerospace environment. However, for its extensive applications, there are still lots of problems to overcome, especially for the irradiation-induced strain in SiC.

In chapter 1, the need for the investigation of irradiation-induced strain or swelling in SiC is reviewed. For SiC-based electronic devices fabrication, ion implantation is widely used for selected-area doping into SiC, which would inevitably induce great strain or swelling. This strain has been found to significantly degrade the mechanical properties and change the electronic properties of the SiC devices. Therefore, an accurate non-destructive evaluation of the residual strain in SiC devices has become increasingly important, in particular with the development of the advanced micro/nano SiC-based devices. However, it is a significant challenge for common strain measurement techniques like X-ray diffraction (XRD) due to their spatial resolution limitation. A non-destructive technique with a high spatial and strain resolution is needed. Besides, the irradiation-induced strain/swelling has been found to be driven by the various defects in SiC. Hence, clarifying the contribution to the strain/swelling of each defect type is important to accurately evaluate the strain or swelling. Moreover, the investigation of irradiation-induced strain/swelling in SiC is also important for its application in nuclear reactor or aerospace, where SiC would also be subjected to various irradiation. In this study, selected-area He^+ ion irradiation was performed on n-type 4H-SiC (0001) single-crystal substrates with an energy of 100 keV at room temperature. In the following chapters, those issues mentioned above were targeted on the basis of a series of experiments.

In chapter 2, a detailed normal strain distribution in the ion-irradiated 4H-SiC was first provided using the non-destructive techniques of electron backscattering diffraction (EBSD) and confocal Raman microscopy (CRM), whose results showed good agreement. This result validated the application of EBSD and CRM to evaluate the detailed strain distribution in selected-area ion-implanted SiC. In addition to the strain introduced in the irradiated area, excessive strain also extended into the surrounding substrate owing to irradiation-induced swelling. Furthermore, a higher compressive strain is concentrated around the interface between the irradiated and unirradiated areas. An anisotropic strain distribution in the irradiated area is also detected using EBSD, which indicates a correlation of strain degree and crystallographic orientation.

In chapter 3, the distribution of irradiation-induced defects in the 4H-SiC was explored using various transmission electron microscopy (TEM) techniques. A great anisotropy of defect distribution was first deduced in the selected-area He^+ ion irradiated 4H-SiC, that interstitial type defects preferentially redistribute into the surface normal direction ([0001] direction) with more negative volume defects locating in the lateral direction ($[10\bar{1}0]$ and $[11\bar{2}0]$ direction), which might account for the detected anisotropic strain using EBSD. This anisotropy decreased upon annealing at 873 K, and it was quite lower in the non-selected-area He^+ ion irradiated 4H-SiC. It was found that great compressive stress was introduced in the lateral direction in the selected-area He^+ ion irradiated 4H-SiC due to the constraint against lateral expansion, and these compressive stresses were introduced at the beginning of ion irradiation. These findings provided a direct evidence that compressive stress was supposed to inhibit the interstitial type defect formation, enhancing the anisotropic defect distribution.

In chapter 4, using TEM and scanning transmission electron microscopy electron energy-loss spectroscopy (STEM-EELS), the correlation of the swelling with various defects, including point defects or tiny clusters, defect clusters, amorphous transition and helium atoms, was separately analyzed. These results provided the volume swelling range for the different defect regions, which is helpful for the prediction of SiC swelling in actual application. A saturation swelling with a value of 2-3% in the near-surface region, induced by point defects or tiny clusters (invisible in TEM), was observed at room temperature. This saturation has already reached at great low dose of about 0.02 dpa (displacement per atom). The swelling of region containing black spots defects ranges from about 3%–7%. Helium atoms in the form of helium bubbles increase the volume swelling at relatively high irradiation fluences. However, decreasing effect of He^+ ion irradiation on volume swelling also seems to be possible as below a certain irradiation fluence.

In chapter 5, the main conclusions and most relevant findings this work are presented and summarized.