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Characterisation of 60° misfit dislocations in SiGe alloy using nuclear microscopy

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Abstract

This paper uses the transmission ion channeling technique on the NUS Singletron accelerator to map misfit dislocations at the interface of a SiGe layer epitaxially grown on a (001) silicon substrate. A bunch of five 60° dislocations and a single dislocation have been studied using a focused 2 MeV proton beam with a spatial resolution of 60 nm and good image statistics. The bent (110) planes due to 60° dislocations cause the image contrast to change asymmetrically while tilting the sample close to the channeling direction.

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Keywords: Misfit dislocation; Transmission ion channeling

1. Introduction

Transmission ion channeling uses a focused MeV ion beam to generate images showing variations in crystal quality along a specific crystal direction [1,2]. High-energy ions follow a channeling process when aligned with a crystal orientation, in which they are steered by the rows and planes of the lattice, so that they travel in regions of lower atomic electron density, and their energy loss rate is therefore reduced. If crystal defects distort the lattice planes, this can produce abrupt changes in the channeling direction, so the originally channeled ions become dechanneled with the higher energy loss rate.

A SiGe alloy has a larger lattice parameter than pure silicon owing to the different lattice parameters of Si and Ge [3]. If a thin layer of SiGe is grown onto a Si substrate, above a certain layer thickness, the strain in the layer is relieved by the formation of misfit dislocations, which are usually 60° dislocations. 60° dislocations locally bend the (110) lattice planes and cause the channeled ions

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to be dechanneled. Therefore, ions passing through the sample with different energies can be measured and images of interested region can be produced.

In this paper, a focused 2 MeV proton beam, generated by a Singletron accelerator [4], has been used to scan the surface of an etched SiGe sample which was thinned about 20 μm thick. Images of a bunch of five 60° dislocations were recorded. Moreover, line scans were applied across this bunch of dislocations to clearly measure the asymmetrical changes of contrast caused by the 60° dislocations while tilting the sample close to the (1 1 0) planar direction.

2. Experimental procedures

Protons transmitted through a thinned SiGe sample with a 2 MeV proton beam scanning the sample surface were detected by an ORTEC ULTRA alpha detector, with a Mylar foil placed in front of it (see Fig. 1). The voltage-pulse output of the detector is amplified by a CANBERRA 2004DM and 2015A amplifiers before being fed into the data acquisition system (OMDAQ). The image is displayed with a pixel resolution of 256×256. In order to improve the data statistics, a longer data acquisition time was selected.

The SiGe sample was mounted on a small, motor-driven rotating stage, which can rotate around the horizontal axis at a small angle of about 0.5°/step. As a result, relevant regions of the sample can be easily reached by the 1-axis rotation stage and 3-axis translation stage.

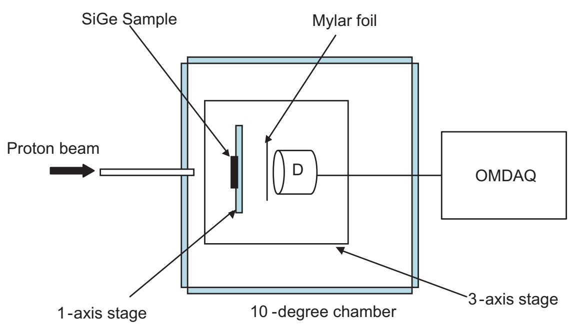

Fig. 1. A schematic of the experimental set-up.

Owing to the restricted chamber geometry without a goniometer to mechanically tilt the sample, small angular changes were made in the beam alignment by shifting the location of the collimation slits of the nuclear microprobe away from the beam axis. A vertical collimator displacement of 25 μm produced a change of 0.02° in the beam alignment with respect to the horizontally-running (1 1 0) planes, comparable to the planar channeling critical angle of Si at 2 MeV protons, $\Psi_p = 0.17°$, and caused no detectable loss of spatial resolution using a beam spot size of 60 nm.

The function of the Mylar foil (see Fig. 1) used here is to block the transmitted protons with energy lower than the pre-set energy value corresponding to the thickness of the Mylar foil. Therefore, by selecting the thickness of the Mylar foil the desired energy threshold of transmitted protons can be chosen. This means that the Mylar energy loss foil stops most non-channeled protons, so that mostly only channeled protons with higher energy are transmitted [5]. Therefore, the lower energy part of the transmitted energy spectrum, which conveys little useful information is not recorded, and only the useful high-energy protons are recorded. As a result, the signal to noise ratio of images is improved, enabling small contrast changes in the images to be resolved. In this paper, the images were taken with the Mylar energy loss foil of 48 μm thickness.

3. Results

A Nomarski image of a portion of the SiGe sample is shown in Fig. 2. A [1 1 0] 60° dislocation cross-arm is seen here, and since a low magnification was used for taking this image, etch pits caused by threading dislocations cannot be seen along the dislocation arms. Fig. 3 shows a transmission channeling image of the same region of the sample with the scan size of 220×66 μm^2, recorded for 38 min. The thinned sample was bent locally owing to the strain in the epilayer. Therefore, the background of the image becomes progressively darker from right to left. Since the

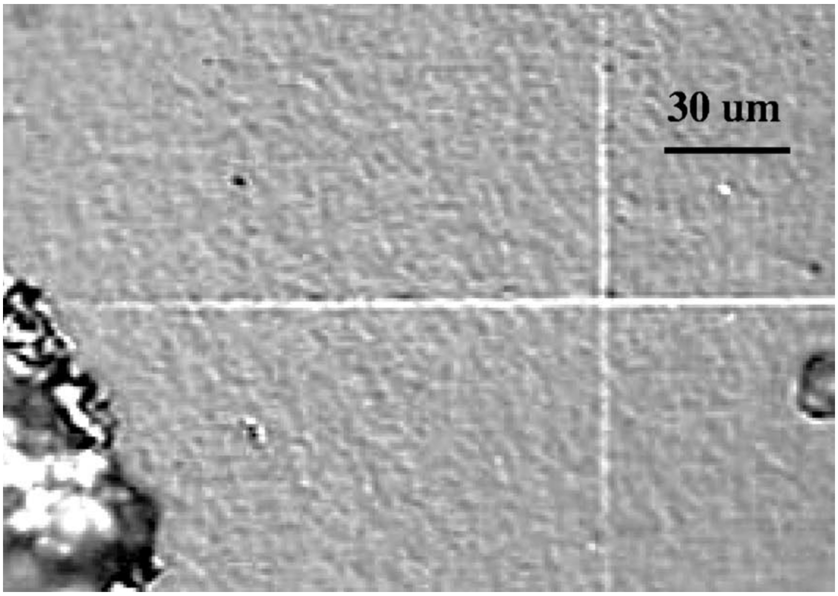

Fig. 2. A Nomarski photograph of the etched SiGe sample with a low magnification.

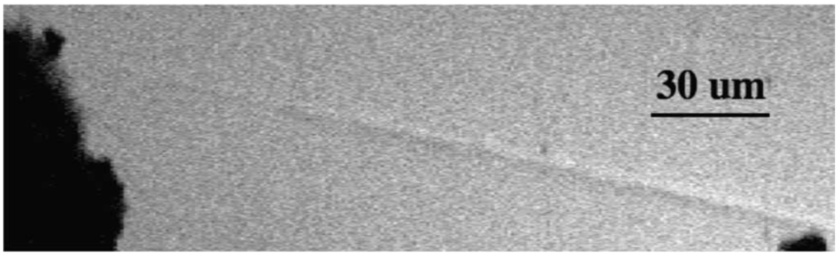

Fig. 3. A transmission channeling image of the SiGe sample with the scan size of $220 \times 66\ \mu m^2$, recorded for 38 min.

proton beam was aligned with the horizontally-running (1 1 0) planar direction only dislocation bands along this direction will be shown in this image. The dark–bright band from left to right across the image caused by the bunch of 60° dislocations in the [1 1 0] direction can be seen.

A region was selected between the fifth and sixth etch pit at which a bunch of five 60° dislocations exists. An image of this region with the scan size of $11 \times 11\ \mu m^2$ is shown in Fig. 4(c). This image was taken at a tilt angle of 0.16° with respect to the (1 1 0) planes. It is seen that the region of the dislocation band is brighter than that of the background, which means that the energy loss of ions passing through this region is lower than that of the surrounding virgin crystal. This is because the [1 1 0] 60° dislocations cause the (1 1 0) planes to become bent by a small angle [6]. As a result, while the bent (1 1 0) planes are tilted towards the ion beam direction the ions are well channeled compared to the surrounding non-bent region. In contrast, at the other side of the tilt angle with respect to the (1 1 0) planes (shown in Fig. 4(a)) the bent (1 1 0) planes cause the ions to become more dechanneled than the surrounding region. Especially, at the normal direction of the sample surface (Fig. 4(b)), the dislocation bunch presents bright–dark contrast. In these images two etch pits, caused by the threading dislocations are clearly seen just under the horizontal dislocation

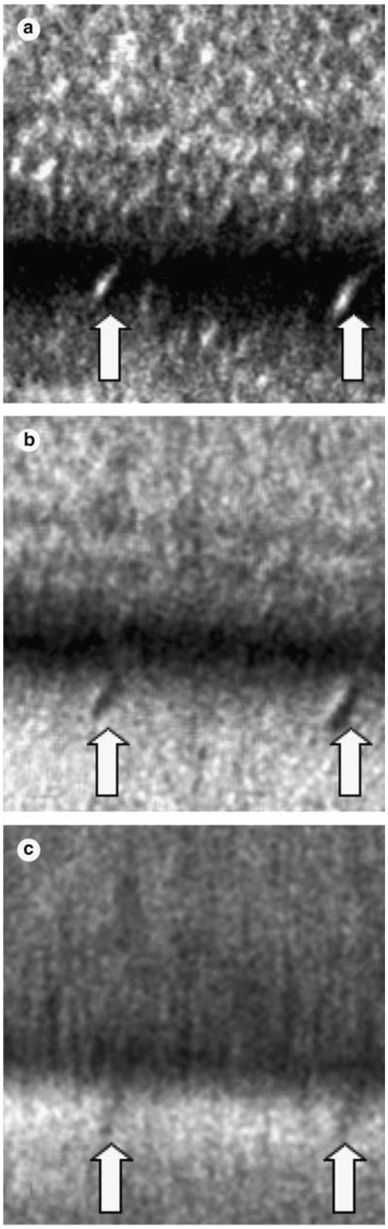

Fig. 4. Three transmission channeling images of the bunch of five 60° dislocations of the SiGe sample with the scan size of $11 \times 11\ \mu m^2$. Three images (dark contrast showing high-energy loss, bright contrast showing low energy loss) were taken at different tilting angles, which are at (a) −0.16°, (b) 0.00° and (c) +0.16°, respectively, with respect to the (1 1 0) planes. Arrows show locations of etch pits.

band and the contrast of two etch pits also changes at different tilting angles. These two etch pits are

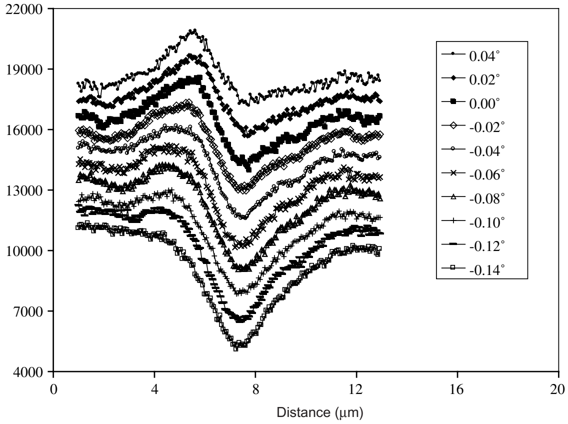

Fig. 5. A graph of line scans of the bunch of five 60° dislocations with various angles with respect to the (1 1 0) planes. Each curve is offset by an additional 1000 counts for clarity.

ideal reference points for locating the same sample area at different tilt alignments.

Vertical line scans were recorded in the middle of these two etch pits for different horizontal tilt angles of the sample with respect to the (1 1 0) planes. Each line scan was recorded for 15 min and the results are plotted in Fig. 5 where it is seen that the image contrast produced by the bunch of five 60° dislocations shows asymmetrical changes with tilt angle. While the beam was tilted to one side of the channeling direction, the arm allowed better channeling than the surrounding non-dislocated region, whilst when tilted to the other side it caused more dechanneling than the non-dislocated region. This further indicates that the 60° dislocations asymmetrically bend the (1 1 0) lattice planes in the epilayer around the dislocation core.

The asymmetrical changes of contrast also can be observed at a single 60° dislocation. Here, the sample was positioned near the right end of the horizontal band shown in Fig. 3. The single dislocation was studied by performing vertical line scans across this region at various angles to the normal direction of the sample surface. Each line scan was taken in 20 min and the results are given in Fig. 6. This asymmetrical effect of the single dislocation can be seen in the line scan spectra, even though it has much weaker contrast than the five dislocations in Fig. 5.

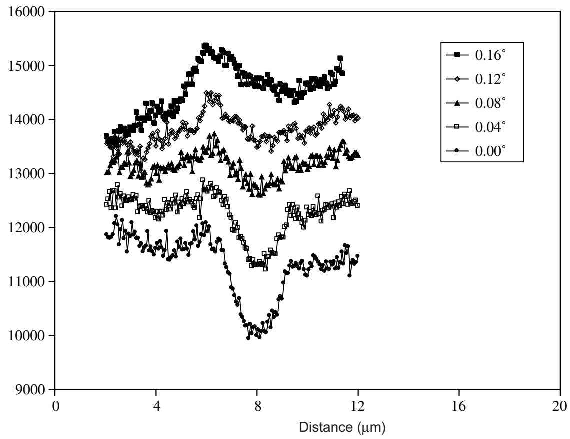

Fig. 6. A graph of line scans of the single dislocation with different angles with respect to the (1 1 0) planes. Each line is offset by 500 counts additionally.

4. Conclusions

60° misfit dislocations are a type of linear crystal defect. Since the bending of crystal planes caused by 60° misfit dislocations is quite small, it is difficult to get images with good contrast [6]. A Mylar energy loss foil of 48 μm thickness has been used here to improve the image contrast. Also, a 2 MeV proton beam with the good spatial resolution of 60 nm was used in this experiment. As a result, changes of image contrast caused by 60° dislocations with various angles with respect to the (1 1 0) planes can be clearly revealed in this paper. However, it is necessary to know the bending effect of the lattice planes and the distorted region of the crystal. We are working on theoretical models, which can simulate the Burger's vector of a 60° dislocation affecting the lattice planes around the dislocation core, and whether Monte-Carlo channeling simulations using such models could reproduce the experimental results.

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