Proximity Effect of High Energy Ion Tracks in Amorphous SiO_2

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We have studied the effect of proximity of ion tracks in amorphous SiO_2 on their chemical etching behaviour. The ion tracks were generated in 2 micrometer thick SiO_2 by irradiation with 185 MeV Au ions and subsequent etching using hydrofluoric acid. Scanning electron microscopy reveals a decrease in the etched track radius below a distance of adjacent tracks of approximately 0.2 microns. Long range strain generated during track formation is a possible explanation for this behaviour.

1. Introduction

As highly energetic heavy ions pass through a material, they can disturb the structure in their paths, leaving behind cylindrical damage zones a few nanometres in radius and microns in length, called 'ion tracks'. The formation of ion tracks is governed by the interaction of the ion with the target electrons [1,2]. The swift heavy ions excite large numbers of electrons, resulting in rapid localised heating facilitated by electron-phonon coupling. The temperature can far exceed the melting temperature of the material, which can lead to local modifications in a narrow region of a few nanometres around the ion trajectory. The subsequent rapid cooling can quench in the modified material forming an ion track.

SiO_2 has been chosen because it is both technologically relevant and well documented. Additionally, fission tracks in quartz and silicate minerals are often used in geochronology and for dating of archaeological objects. In amorphous SiO_2 the density difference between the track and the unaffected material is of the order of 3%. This small variation, combined with the amorphous nature of both the track and background material renders direct observation of the tracks difficult [3].

Often the material in the ion track shows enhanced chemical etching when compared to undamaged material. This can lead to conical etch pits in the micrometer size range that are easily imaged using scanning electron microscopy (SEM). In this paper, we have used SEM to study the effect of proximity on the size of etched ion tracks in amorphous SiO_2. The technique developed in this paper provides another means for the continuing research to develop a more detailed understanding of ion track properties.

While the work itself is of fundamental nature, it has implications for areas such as nanofabrication, nuclear physics, geochronology, archaeology, and interplanetary science. In particular the materials system under investigation (SiO_2/Si) is of high relevance for the semiconductor industry.

2. Experiment

2.1 Sample preparation

The ion tracks were produced in commercially available 2 µm thick layers of a-SiO_2, thermally grown on Si(100) substrates. The irradiation was performed at the ANU Heavy Ion Accelerator Facility by irradiation with Au ions at 185 MeV, with a fluence of 1×10^9 ions/cm^2. The irradiation was performed at room temperature with the incident ion at normal to the sample surface. Subsequently the samples were etched in 5% HF for 5 minutes at room temperature.

The etching is accelerated in the ion track region, which leads to the formation of conical holes centred around the tracks. The unetched tracks have a diameter of the order of ten nanometres [3] and the etched diameter is typically hundreds of nanometres. These etched holes can be directly observed by using SEM.

2.2 SEM analysis

Example SEM images of the etched ion tracks are shown in Figure **1**. The holes created by etching the tracks appear as the dark regions. Figure 1a shows a top view image, such as those used in the analysis. Figure 1b shows a side view, displaying the conical nature of the holes. It is readily apparent that isolated tracks leave approximately equal sized holes, while adjacent tracks in close proximity leave smaller holes.

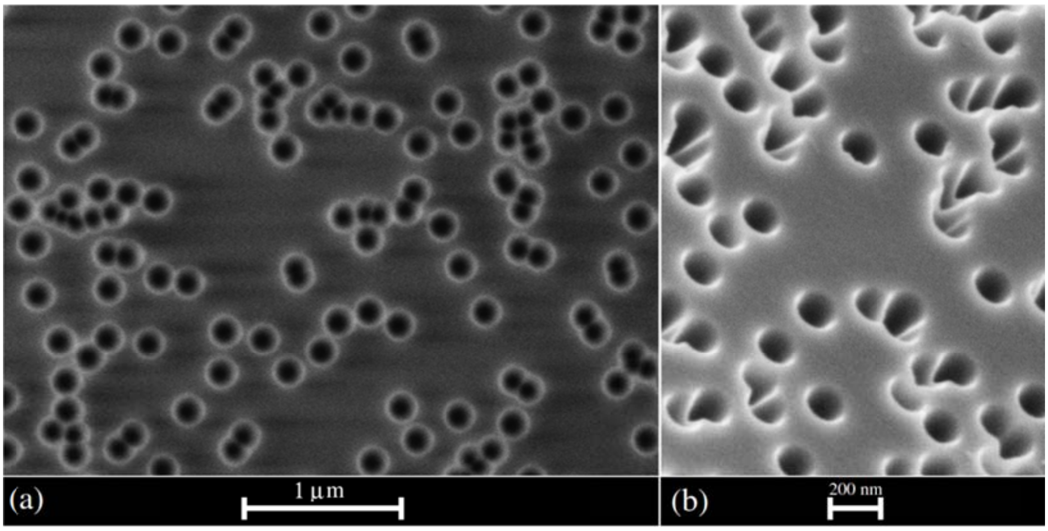

Fig. 1. (a) SEM top view image of etched ion tracks in a-SiO_2, (b) SEM side view image

Analysis of the images was performed using built in functionality of the open source software package *ImageJ* [4]. First the image was converted to a binary form based on brightness thresholds, which are set to select the dark central spots of the etched tracks. The bright rings around these holes enable reproducible and accurate thresholding. Images in binary form lend themselves well to automated particle analysis and particle counting.

The specific measured sizes of the individual etched tracks are somewhat dependent on the thresholding conditions, however, provided they are consistent, the analysis technique provides a means to compare the track sizes across many images. Additionally the etching conditions, while uniform across the sample, will also arbitrarily affect the size of the etched tracks.

The automatic particle analysis returns the x-y coordinates of the centre of each track, as well as its area. The holes were assumed to be approximately circular, allowing the radius to be approximated from the area. For each hole, the Pythagorean distance was found to the nearest neighbour.

3. Results and discussion

Figure 2 shows a plot of the nearest neighbour distance as a function of the etched track radius. Two approximately linear regions are apparent from Figure 2. In the first region, above a nearest neighbour distance of 0.2 µm, the average etched track radius is constant at about 0.08 µm. At nearest neighbour track distances below 0.2 µm, a linear decrease of the etched track radius is apparent, suggesting that adjacent tracks separated in this distance range influence their respective etching behaviour. Importantly, this effect occurs before the etched tracks overlap. A possible explanation for this behaviour can be modification of the etching rate by strain induced from tracks in the vicinity. Ion tracks in amorphous SiO_2 have been described as frozen in pressure waves which produce local strain fields in the material [5].

For etched track radii below approximately 0.06 µm there appears to be another region of greater slope in Figure 2. This is likely governed by tracks influenced by multiple close neighbours, which is not taken into account in the single nearest neighbour graph. At the given low irradiation fluence, however, the number of tracks influenced by multiple neighbours is small and thus not significant in the presented statistics.

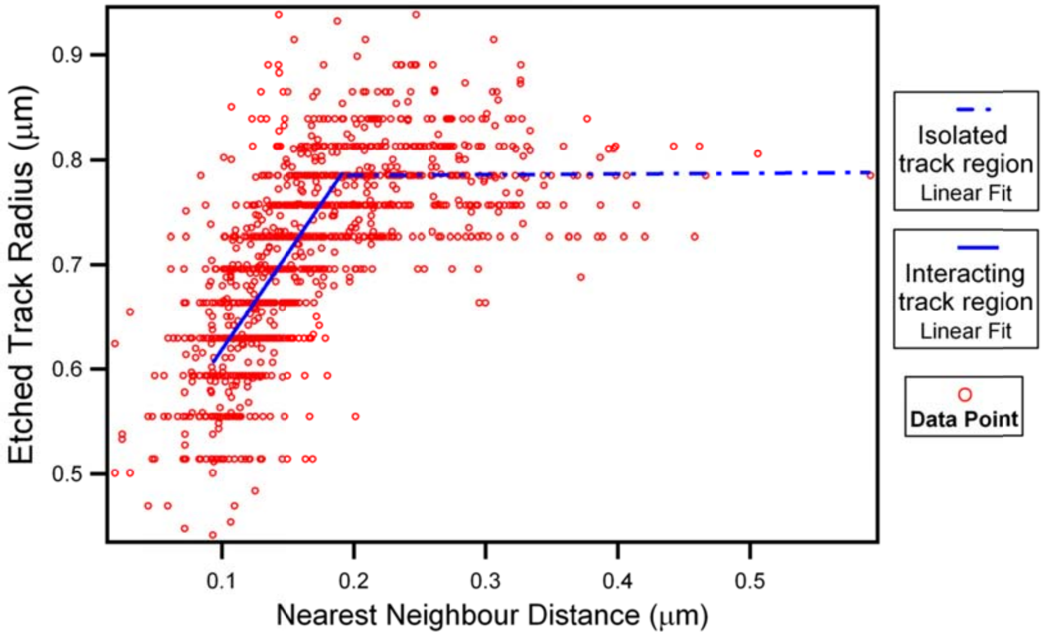

Fig. 2. Etched track radius plotted as a function of the nearest neighbour distance, and linear least squares fits of the two major regions.

The analysis was performed on images at various magnifications. At higher magnifications the size of the etched tracks can be measured more accurately, however fewer tracks can be measured in each image. At lower magnifications we could measure far more tracks simultaneously, however the pixel size constrains how accurately the track size can be measured. These pixel size limitations are responsible for as the horizontal lines in the data points in Figure 2. The data points from both the high and low magnifications agree, and allow a compromise between the number of measurements, and the accuracy of these measurements.

From Figure 2 we are able to observe the effects of proximity of neighbouring ion tracks at distances far greater than the actual unetched track diameter of approximately 10 nm [3]. The specific etching conditions chosen are somewhat arbitrary, and more experiments with varying etching times and irradiation fluences are currently in progress. Such experiments will be able to yield more detailed information about the strain generated during high-energy ion irradiation, and thus a better understanding of the ion track generation process.

4. Conclusions

We have analysed SEM images of etched ion tracks in amorphous SiO_2 to study the effect of their proximity on the etch radius. The tracks were found to influence each other at distances below 0.2 µm. This is beyond both the actual track diameter as well as the etched track diameter, which are approximately 10 nm and 1.8 µm, respectively. This indicates that this influence is unlikely to be a result of the particular etching conditions used, and is likely the result of strain in the material created by the formation of the track. Extending the investigations of this project to different implantation and etching conditions, as well as different materials, will yield more detailed information about the strain generated during track formation, and ultimately yield a better understanding of the ion track properties.

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