**Investigation of Radiation Damage and Diffusion of Xenon Implanted in 6H-SiC**

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**Abstract**

Radiation damage and diffusion behaviour of xenon implanted in 6H-SiC has been investigated using Rutherford backscattering spectrometry (RBS) and channelling techniques. Implantation at 600oC caused the 6H-SiC to retain its crystallinity but with some damage in the implanted region. Vacuum-annealing of radiation damage was performed for 5h in the range 1000 to 1500ºC in steps of 100 ºC. There was no diffusion detected during annealing from 1000oC to 1400oC; only a shift of the xenon profile towards the surface was observed at 1400oC, perhaps due to thermal etching. Diffusion was observed at the annealing temperature of 1500oC also with a shift towards the surface.

**Introduction**

In modern high temperature nuclear reactors, silicon carbide (SiC) is used as the main diffusion barrier for the fission products in the coated fuel called TRISO particles. In the TRISO particle, pyrolytic carbon and SiC layers retain most of the important fission products like xenon, krypton and cesium effectively at temperatures up to 1000oC, with the release of silver raising doubts on the effectiveness of SiC layer [1].

Previous studies [2, 3] have shown that room temperature implantation of heavy ions into single crystal 6H-SiC causes the SiC to become amorphous. However, the SiC remains crystalline with many point defects and dislocation loops (damage) for 400 to 600oC implantations. The recovery of SiC material upon annealing depends on both the amount of damage created during implantation as well as the annealing temperature [4].

K Fukuda *et al.* [2] suggested that the release of Xe at annealing temperatures below 1200oC was due to interstitial diffusion and release of Xe from trapping sites (vacancies and dislocation loops). At temperatures ranging from 1200oC to 1400oC, grain boundary diffusion was the dominant mechanism, while above 1400oC the release is governed by the normal volume diffusion without any hindrance of trapping effects [2].

In this study two phenomena in single crystal 6H-SiC implanted by 360 keV Xenon ions are studied using Rutherford Backscattering Spectroscopy (RBS) and channelling:

* Radiation damage: its annealing behaviour at annealing temperatures ranging from 1000oC to 1500oC.
* Diffusion of xenon in 6H-SiC at these annealing temperatures.

**Experimental Procedure**

Xenon ions were implanted in a single crystalline wafer (6H-SiC) with 360keV at 600oC with a fluence of 1 × 1016 cm-2. A normal incident angle was tilted 7o off to reduce channelling. To prevent beam induced target heating, the dose rate was kept below 1013 cm-2 s-1 .The sample was vacuum annealed in a computer control Webb 77 graphite furnace at different temperatures for the same time, of 5h. Depth profile were obtained by Rutherford backscattering spectrometry (RBS) using α-particles with 1.6MeV. The same set up was use to investigate radiation damage of 6H-SiC sample by channelling spectroscopy.

**Results and discussion**

**Figure 1:**  *The random and aligned Rutherford backscattering spectra of 6H-SiC implanted at 600oC compared with the as-implanted xenon peak.*



**Figure 2:** *Random and aligned Rutherford backscattering spectra of 6H-SiC implanted at 600oC and submitted to isochronal annealing of 5h*.

Implantation of 6H-SiC at 600oC retained the crystallinity of 6H-SiC with some damage remaining in the implanted region . The damaged region is indicated by the broad peak around 150nm in the RBS spectra compared with the unimplanted sample as shown in Figures 1 and 2. Figure 1 shows that the implanted xenon created damage near the surface of 6H-SiC. It also shows that the xenon peak corresponded with the damage peak. During implantation the xenon atoms were mobile due to their high energy, which enables them to displace atoms causing radiation damage. The results show the radiation hardness of SiC during implantation at high temperatures. Similar radiation hardness of SiC was reported for heavy implanted ions at temperatures above 400oC [4].

Isochronal annealing of the sample implanted at 600oC from 1000oC to 1400oC for 5h caused some annealing of the radiation damage with retention of some defects. This was the result of the defects annealing into dislocation loops and other extended defects during the first annealing cycle that are hard to anneal out. The annealing of some defects is indicated by the reduction of the broad peak around 150nm (Figure 2). At 1500oC the damage pick disappears but the virgin spectrum was still not achieved due to retained implanted Xe and some damage.



**Figure 3:** *Xenon profile in 6H-SiC implanted at different temperatures compared to SRIM11 prediction.*

**Table 1:** *Projected range values obtained from Genplot [5] by fitting experimental values to the Edgeworth distribution, and from SRIM11[6]* .

|  |  |  |  |
| --- | --- | --- | --- |
|  | **23oC** | **600oC** | **SRIM11** |
| **Rp (nm)** | 112.4 | 113.8 | 101 |
| **ΔRp(nm)** | 28.7 | 35.3 | 24.0 |
| **Skewness** | 0.4 | 0.6 | 0.1 |
| **Kurtosis** | 2.7 | 3.0 | 2.6 |

The projected range of 360 keV xenon ions implanted at room temperature agreed, within experimental error and within the accuracy of SRIM11, with the SRIM11 prediction, with the room temperature implantation being slightly deeper. The projected range straggling ΔRP was also slightly larger due to experimental error and/or channelling. The skewness and kurtosis of the implanted profile were nearly equal to the SRIM11 predictions.

Comparing the Xe RBS spectra for implantation at 600oC to the room temperature implanted samples showed that a signified loss of xenon took place during implantation at 600oC, i.e. there was a reduction of the xenon peak area under the curve and a broadening of the implanted profile (i.e. an increase in ∆Rp ). This loss was probably due to radiation-induced diffusion.

**Table 2*:*** *The projected range RP and projected range straggling ΔRP values obtained from Genplot by fitting a Gaussian distribution to the experimental data.*

|  |  |  |
| --- | --- | --- |
| **Temperature (oC)** | **Rp(nm)** | **∆Rp(nm)** |

Un-annealed 113.8 35.3

1000 111.0 34.3

1100 114.9 34.5

1200 119.0 36.8

1300 115.8 35.8

1400 90.2 35.3

1500 95.9 42.5



**Figure 4:** *Xenon depth profile in 6H-SiC implanted at 600oC after isochronal annealing.*

From Table 2 and Figure 4 the RBS spectra showed no broadening of the xenon peak for isochronal (5h) annealing from 1000oC to 1300oC. Thus no diffusion is taking place at these temperatures. At 1400oC xenon tended to shift towards the surface perhaps due to thermal etching, with no sign of any broadening of the Xe peak, i.e. no diffusion taking place.

Annealing at 1500oC for 5h caused the xenon profile to shift towards the surface accompanied by a broadening of the peak, indicating that diffusion was taking place at this temperature.

**Summary**

Radiation damage created in 6H-SiC by bombardment of 360 keV xenon ions at a substrate temperature of 600oC was investigated using RBS channelling. It was found that the implantation of xenon at 600oC caused the 6H-SiC to retain its crystallinity with some distortions near the surface region. Vacuum-annealing of radiation damage was performed for 5h in the range 1000 to 1500ºC in steps of 100 ºC. Annealing of the radiation damage took place with the increase in annealing temperatures. The rate of annealing out of the damage depended on the temperature of annealing i.e. At 1000oC small amount of damage was annealed out while at 1500oC the damage was almost completely annealed out. Thus at 1500oC the damage pick disappears but the virgin spectrum still not achieved due to retained Xe and damage.

For comparison with SRIM11 predition, we found that RBS-measured room temperature implantation profile agreed within the experimental error with the SRIM11 simulated profile. Comparing the 600oC implantation profile with the room temperature implanted profile indicated that diffusion took place during implantation and there was loss of the implanted species.

No diffusion took place in the annealing temperature range of 1000 to 1300oC. At 1400oC, a shift of the xenon profile towards the surface, which might be due to thermal etching, was observed. Annealing at a temperature of 1500oC, showed a shift towards the surface accompanied by broadening and reduction of the xenon peak, indicated that diffusion taking place.

**References**

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