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Mobility of Hg^+ and Br^+ Implanted in Quartz

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Abstract

Both Hg^+ and Br^+ were implanted in quartz (SiO_2) 7 years ago. The mobilities of the implanted Hg^+ and Br^+ at room and higher temperatures are investigated by Rutherford backscattering of 2·1 MeV He^{2+} ions. The results show that both Hg^+ and Br^+ are still immobile at room temperature after 7 years. The depth distributions of Hg^+ agree well with those calculated by the transport of ions in matter program (TRIM'90). However, for the case of Br^+ the mean projected range is shallower than the TRIM'90 prediction with increasing implantation energy. It is found that 300 keV Hg^+ and 250 keV Br^+ are mobile after 600°C and 500°C annealing respectively. Both diffusion and evaporation during annealing are observed.

1. Introduction

Implantation profiles in semiconductors, insulators and metals have been measured for a large variety of ions ranging from light ones, such as a lithium and boron, up to very heavy ones such as Bi (Fink *et al.* 1985; Grande *et al.* 1987). The stability of implanted ions in solids is a question of interest. Several gaseous ions implanted into solids show a special behaviour. Fink *et al.* observed the mobility of nitrogen implanted into magnesium and aluminium at room temperature. Remeasurement in other metallic samples from 6 months to 4 years after implantation shows that nitrogen is mobile in those systems as well. Boron also exhibits room temperature mobility in copper and nickel (Fink *et al.* 1989). Behar *et al.* reported that Ar, Kr and Xe are partially mobile in photoresist films and the mobility is strongly dependent on the mass of the implanted ions. They also found that He diffuses rapidly when implanted into Mylar (Behar *et al.* 1990). Again Fink *et al.* (1988) reported that ^3He implanted into Mylar is found to be mobile at room temperature. In the periodic table of elements, only Hg and Br are heavy liquids at room temperature. An interesting question arises: would Hg^+ and Br^+ implanted in solids behave similar to some gaseous ions?

Ion implantation has been used to produce optical waveguides in many crystals (Wang *et al.* 1994). Crystalline quartz is an ideal substrate. Waveguide and second harmonic generation have been observed in quartz (Chandler *et al.* 1988).

In 1986–87 we reported the measurement of depth profiles of Hg^+ and Br^+ implanted in quartz and compared the experimental values with our calculation procedure based on Biersack's (1981, 1982) angular diffusion model for the mean projected range R_p and range straggling ΔR_p (Wang *et al.* 1987, 1988).

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The main objectives of the present work were to remeasure by Rutherford backscattering the depth distributions of Hg^+ and Br^+ implanted into quartz several years ago and to compare them with a TRIM'90 calculation (Biersack and Haggmark 1980), and to discuss the stability and thermal behaviour of Hg^+ and Br^+ implanted in quartz.

2. Experiment

Samples were implanted several years ago and still remain. The samples used were amorphised by Ar^+ irradiation with a dose of 2×10^{15} ions/cm^2 at different energies. The maximum thickness of the amorphised quartz layer was estimated to be 260 nm. This layer was thick enough to stop 400 keV Hg and Br ions in quartz. To minimise the sputtering effect on the ion distribution and ensure sufficient sensitivity for determining impurities, a dose of 2×10^{15} ions/cm^2 was chosen. All implantations were performed at room temperature, with the beam density kept to less than 1 μA/cm^2 to avoid excessive heating of the sample. In order to obtain uniformity over the implanted area, a two-directional electrostatic system for parallel scanning was used. A neutral trap was also employed.

For investigating the thermal behaviour of Hg^+ and Br^+ ions implanted in quartz, samples were annealed at various temperatures between 300°C and 600°C for 30 min in N_2 ambience.

The depth distributions of implanted Hg^+ and Br^+ were measured by Rutherford backscattering (RBS) using a 2·1 MeV He^{2+} ion beam at normal incidence with a scattering angle of 165°. The backscattered He^{2+} ions were detected with a Si-surface barrier detector. The beam current of He^{2+} impinging on the target was about 30 nA. In order to determine the Hg and Br surface positions, we used Au film and KBr for calibration. The error assignment was determined at ±2 channels. Each channel was equal to 4 and 4·1 nm depth for normal incidence in the case of Hg^+ and Br^+ respectively. The ion implantation was carried out using a 400 kV implanter made at Shandong University. The RBS was performed using a 1·7 MV tandem accelerator at Shandong University.

3. Results and Discussion

In order to convert the RBS energy spectra into depth distributions, we have used the surface energy approximation and stopping cross section data by Chu *et al.* (1978). The depth distributions of implanted Hg^+ and Br^+ were computer fitted in order to obtain the position and full width at half maximum (FWHM) of the energy peak. The range straggling was calculated after deconvolution under the usual assumptions that the estimated energy straggling of He^{2+} in quartz and the system resolution are both Gaussian.

Some factors may affect the implantation profile such as channelling, dose and sputtering. To our knowledge, there are no data on the sputtering yields of the quartz induced by Hg^+ and Br^+ ions. In order to get some information on the sputtering yield, we have used the TRIM code to simulate it. The sputtering yields are 0·5079 and 1·54 atoms per ion for Si and O respectively in the case of 300 keV Hg^+ implanted into quartz, and 0·3065 and 0·5806 atoms per ion for Si and O respectively in the case of 400 keV Br^+ implanted into quartz. The estimated sputtering thicknesses are 3·5 and 1·3 nm. This causes an error in the range measurement of 3% and 1% for Hg^+ and Br^+ respectively.

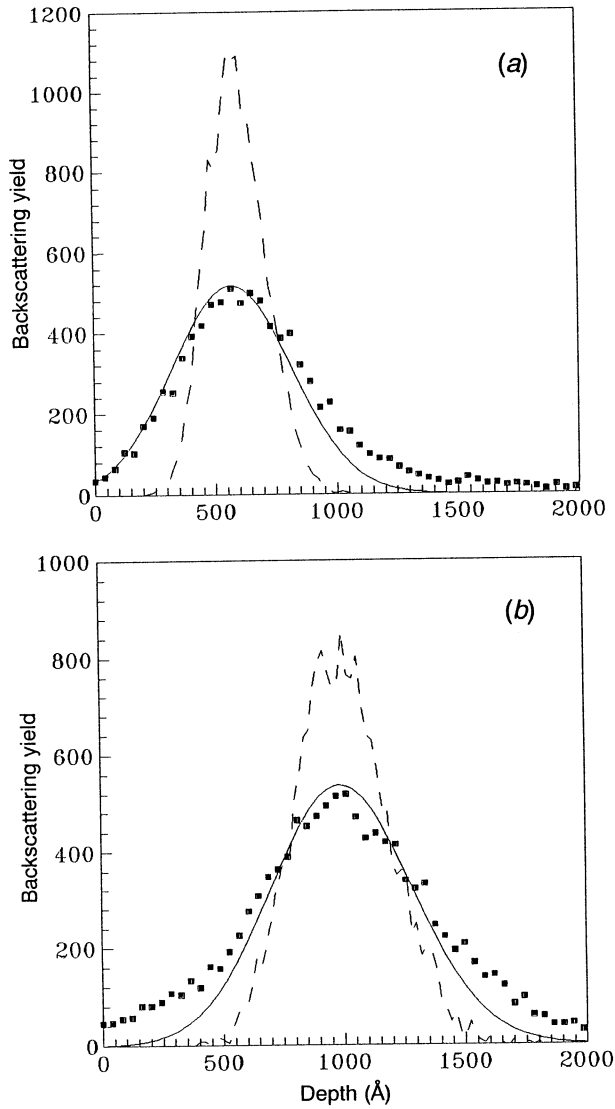

Fig. 1. Comparison of experimental data for the depth distribution with the TRIM'90 simulation for (*a*) 150 keV and (*b*) 300 keV Hg^+ implanted in quartz. The squares show the experimental data. The dashed curve represents the TRIM'90 prediction and the full curve is the prediction convoluted with the experimental detector resolution. In (*b*) the number of ions in the TRIM'90 simulation is 4479.

Fig. 1*a* shows a comparison of the experimental depth distribution with the TRIM'90 prediction for 150 keV Hg^+ implanted into quartz. The squares represent the experimental data obtained by RBS with $2 \cdot 1$ MeV He^{2+} ions. The dashed curve represents the TRIM'90 prediction. In order to increase the statistical accuracy, the number of ions in the TRIM'90 simulation was 9600. It was found that the peak positions of the experimental and theoretical distributions are consistent

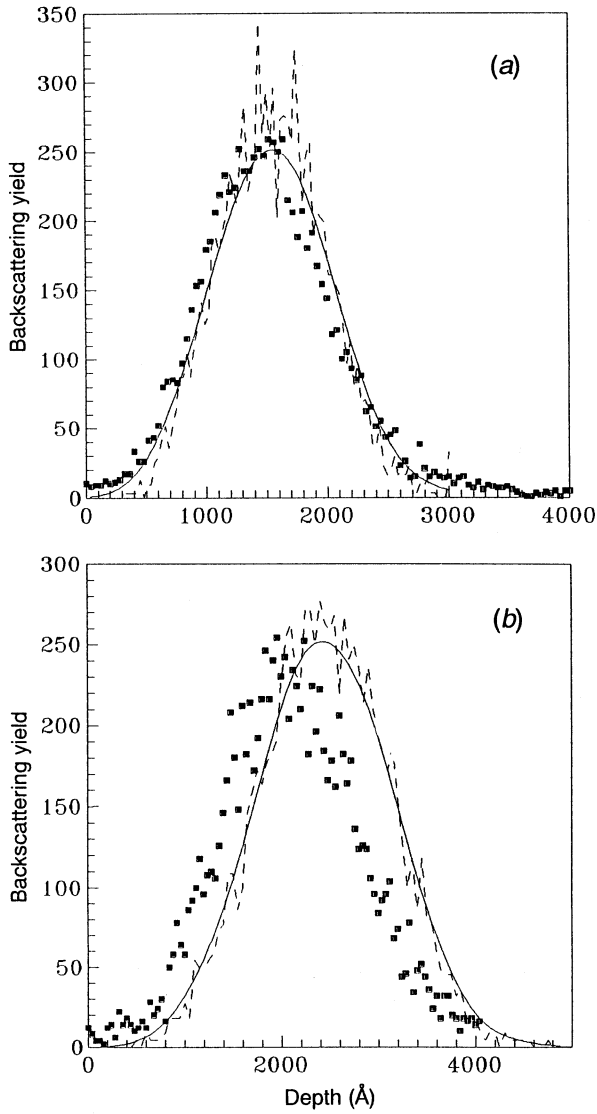

Fig. 2. Comparison of experimental data for the depth distribution with the TRIM'90 simulation for (*a*) 250 keV and (*b*) 400 keV Br^+ implanted in quartz. The squares show the experimental data. The dashed curve represents the TRIM'90 prediction and the full curve is the prediction convoluted with the experimental detector resolution. The number of ions in the TRIM'90 simulation is (*a*) 4051 and (*b*) 6493.

within the experimental error. The experimental depth distribution is broader than the depth distribution predicted by TRIM'90. In Fig. 1*a* the original histograms were convoluted with the experimental detector resolution, the full curve agreeing well with the experimental data. The overall agreement with the theoretical prediction seems reasonable; however, there are some deviations in the FWHM.

Table 1. Mean projected range R_p and range straggling ΔR_p of Hg^+ and Br^+ in quartz
The calculated values are obtained from the TRIM'90 code

Energy (keV)	Ion	Experimental value (nm)		Calculated value (nm)	
		R_p	ΔR_p	R_p	ΔR_p
150	Hg	64·8	15·0	60·0	11·9
300	Hg	97·2	24·6	98·7	19·4
250	Br	139·1	42·9	153·3	43·6
400	Br	199·0	55·6	246·2	66·1

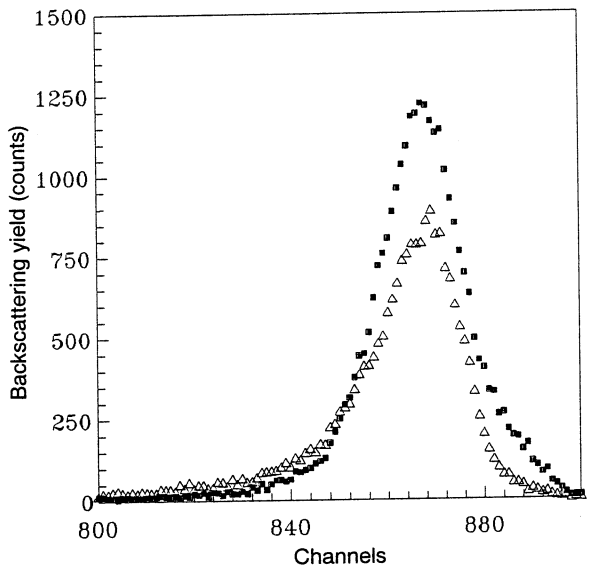

Fig. 3. Comparison of depth profiles for 300 keV Hg^+ implanted in quartz at room temperature (squares) and after 600°C annealing (triangles) in nitrogen ambience for 30 min.

Fig. 1*b* gives a comparison of the experimental data with theoretical prediction for 300 keV Hg^+ in quartz. The peak positions of the experimental and theoretical distributions are consistent within the experimental error. The experimental depth distribution is broader than the depth distribution predicted by TRIM'90. The full curve represents the results convoluted with the experimental detector resolution. The result indicates that the TRIM'90 code predicts the experimental mean projected range very well, but the experimental range straggling is larger than the calculated one in this case.

Fig. 2*a* gives the experimental data and theoretical prediction by TRIM'90 for 250 keV Br^+ implanted in quartz. The squares and dashed curve represent the experimental data and theoretical prediction respectively. It is observed that the form of the experimental depth distribution is quite consistent with the one predicted by TRIM'90. Fig. 2*b* shows the depth distribution for 400 keV Br^+ implanted in quartz. Some deviation of the mean projected range from the TRIM'90 prediction is observed with increasing implantation energy. However,

good agreement between the experimental range straggling and the calculated values is obtained. The form of the depth distribution is consistent with the one predicted by TRIM'90.

One purpose of this work is to check on the stability of the implanted Hg^+ and Br^+ at room temperature. The stability can be characterised by the peak position and full width at half maximum of the depth distribution of the implanted ions. The experimental mean projected range R_p and range straggling ΔR_p are compared with our published data again. The result indicates that these data are consistent with previously published data within experimental error. We conclude that the implanted Hg^+ and Br^+ have remained stable after being kept at room temperature for 7 years. The mean projected range and range straggling obtained are compared with the TRIM'90 code in Table 1.

In Fig. 3 we show the depth profile for 300 keV Hg^+ implanted in quartz to a dose of 5×10^{15} ions/cm^2 before and after annealing. It is found that there is no obvious mobility of Hg towards the surface, but some of the implanted Hg has been lost. This phenomenon could not be described adequately by normal diffusion. The reason is probably due to evaporation.

We have also studied the thermal behaviour of 300 keV Br^+ implanted in quartz. After 300°C annealing the depth distribution obtained is the same as that before, showing that the implanted Br^+ is still immobile. Fig. 4 depicts the thermal behaviour of 250 keV Br^+ after 500°C annealing. No obvious mobility of Br^+ to the surface is observed, but Br obviously diffuses to the inside surface. This suggests that diffusion takes place and has accompanied the evaporation of the implanted Br^+.

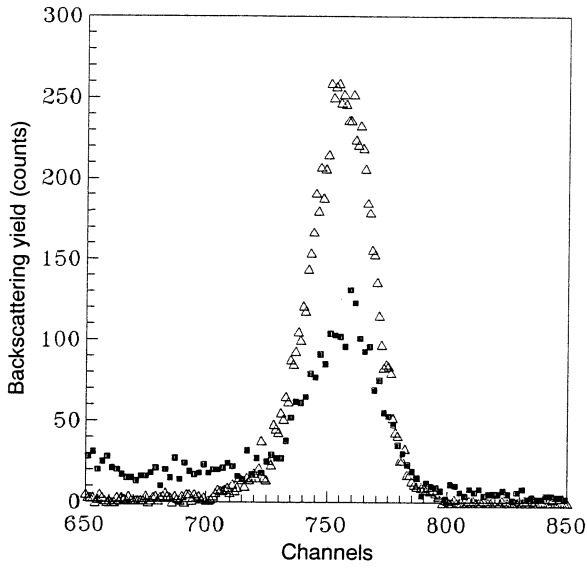

Fig. 4. Comparison of depth profiles for 250 keV Br^+ implanted in quartz at room temperature (triangles) and after 500°C annealing (squares) in nitrogen ambience for 30 min.

4. Summary

The depth distributions of Hg^+ and Br^+ implanted in quartz 7 years ago were remeasured by Rutherford backscattering of 2·1 MeV He^{2+} ions. The experimental depth distributions were compared with TRIM'90 predictions. The results show that the theoretical distributions predicted by TRIM'90 are in good qualitative agreement with measured distributions after the original histograms were convoluted with the experimental detector resolution. TRIM'90 describes the experimental data well for Hg^+ implanted in quartz, except for a small discrepancy in the full width at half maximum of the profile. For the case of Br^+, the mean projected range obtained is shallower with increasing energy than that predicted by TRIM'90, but good agreement between the experimental and calculated values of the range straggling is found. A comparison of present and previous measurements shows that both Hg^+ and Br^+ implanted in quartz remain stable at room temperature. After the annealing at higher temperatures, the amount of implanted Hg^+ and Br^+ is decreased. This phenomenon cannot be described by normal diffusion only. One possible explanation is evaporation at the surface following diffusion.

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