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ABSTRACT

Ion beam mixing in Pt-Si bilayered samples was measured during irradiation with projectiles ranging in mass from 4 amu (He) to 131 amu (Xe) at 10 K, 300 K and 373 K. Using deposited damage energy as a basis for comparing the different irradiations, it was found that the heavier ions were more efficient than the lighter ones for inducing mixing. Moreover, it was observed that the mixing was essentially independent of temperature below 373 K. These results are interpreted on the basis that the mixing is caused by the stimulated motion of defects during the cooling phase of energetic cascades.

INTRODUCTION

Theoretical attempts to explain the low-temperature diffusion of solids during ion irradiation have had little success. The collisional mixing theory of Sigmund and Gras-Marti [1], for example, greatly underestimates the magnitude of diffusion; moreover, it incorrectly predicts a shift of light impurities relative to heavy ones [2]. A second collisional theory, which was proposed by Matteson et al. [3], and which is based on a "random flights" model, is able to predict the magnitude of mixing; however, it predicts also that light marker atoms should diffuse substantially more than heavy ones and this is contrary to observation [4]. To overcome the failures of ballistic mixing theories, Sigmund has recently proposed that the large magnitude of mixing arises from the migration of defects produced in energetic displacement cascades [5]. In reference 5, it seems to be implied that the defect motion results from a thermally activated process. This would be difficult to reconcile with the observations that the magnitude of mixing does not dramatically decrease when the specimen is cooled to very low temperatures, 10 K [6,7], for which thermally-induced defect motion is thought to be suppressed. The theory itself however, only requires that defects have some mobility within the cascade region. An alternative mechanism to thermally-induced defect motion is defect motion which is stimulated by the agitation of the lattice during the cooling phase of the cascade. There is both experimental [8] and theoretical [9,10] evidence that such stimulated motion is important in cascades. In this model both the production of defects and their stimulated motion is required for low-temperature diffusion. To explore this possibility, mixing was measured for the cases that: 1) defects are produced in isolated low-energy recoil events, and 2) defects are produced in energetic displacement cascades. Specifically, the experiments consisted of measuring the interdiffusion of Pt-Si diffusion couples during irradiation with projectiles ranging in mass from 4 amu (He) to 131 amu (Xe) at temperatures between 6 K and 373 K. The He irradiation produces defects (i.e. Frenkel pairs) mostly in low-energy recoil events, whereas the Kr and Xe irradiations produce them in energetic displacement cascades. The measurements at the higher temperatures were carried out to investigate the influence of thermally-induced defect motion on mixing.

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EXPERIMENTAL

The interdiffusion of the irradiated Pt-Si bilayered specimens was measured at different temperatures using backscattering spectrometry. In the present experiments only a 300-keV He beam was available for in-situ analysis of the specimens after irradiation at 10 K. Although the spatial resolution of backscattering for a 300-keV He beam is not optimal, it was sufficient for the present purposes. The Pt and Si were sequentially vapor deposited onto sapphire substrates using electron beam heating in a cryo-pumped vacuum system which has a base pressure of $\sim 1 \times 10^{-7}$ Torr. Pt was chosen for one of the layers in the diffusion couple in order to produce cascades with high energy density. Si was used as the cover layer as it has a low sputtering yield compared to Pt; and also because the energy loss of heavy 300-keV particles in traversing the Si layer is small so that they could penetrate well beyond the Pt-Si interface. The specimens were cooled by clamping the sapphire substrate to the copper tailpiece of the cryostat. Indium was inserted between the sapphire and cryostat to prevent the sapphire from cracking under the applied load.

The irradiation doses were converted from ions/cm² to damage energy/A-cm² at the interface using a modification of the Monte Carlo computer simulation, TRIM [11]. The results of these calculations are illustrated in Fig. 1. The average damage energy on the two sides of the interface was used to normalize the different particle irradiations. This procedure introduces some ambiguity since the relative damage energies of the particles in the Pt and Si are not exactly the same; however the differences are small.

FIG. 1. Calculated damage distribution in Si-Pt diffusion couples.

RESULTS AND DISCUSSION

The mixing at the Pt-Si interface was quantified by subtracting the backscattering spectrum for each specimen prior to irradiation from the corresponding spectrum for the irradiated specimen. The magnitude of the

difference in each channel was then summed over all channels. These integral yields were used as a measure of the mixing. By comparing the integral yields to corresponding yields obtained by computer simulation, the thickness of the mixed layers could be deduced. For convenience it was assumed that the mixed layers were entirely Pt_2Si . The details of this procedure are published elsewhere [6].

The results for the different irradiations are listed in Table I. Since the same deposited 'amage energy was not employed for all the irradiations, the quantity t^2/ϕ , where t is the effective layer thickness of Pt_2Si formed. This quantity, or mixing parameter, has been found to be independent of dose for nearly all cases of ion beam mixing, and this behavior is consistent with the measurements here. It can be observed in the table that t^2/ϕ increases as the mass of the projectile increases. This behavior is illustrated in Fig. 2. Here we have formed the ratio of the mixing parameter for each irradiation with that of Kr. This ratio is referred to here as the efficiency of mixing, i.e.,

$$\epsilon_i = (t^2/\phi)_i / (t^2/\phi)_{Kr}. \quad (1)$$

TABLE I. Ion beam mixing parameter for various projectile irradiations at different temperatures.

	10 K	$t^2/\phi^a)$ 293 K	393 K
300-keV He	0.36	0.44	0.30
225-keV Ne	0.63		
250-keV Ar	0.84	0.91	
275-keV Kr	1.38	1.80	
300-keV Xe	1.37	1.40	1.20
160-keV Xe	1.50		

a) in units of $10^3 A^5/eV$

It was noted above that He irradiation produces defects mostly in low-energy recoil events and that Kr and Xe produce them in dense zones, and therefore plotting the efficiency as a function of projectile mass provides some indication of the dependence of mixing on cascade energy density. The overall dependence of the mixing on energy density seems consistent with the hypothesis that stimulated motion of defects in energetic cascades is an important aspect in low-temperature ion beam mixing.

Two features of the efficiency curve warrant further discussion: 1) the efficiency for 300-keV He irradiation is not zero; and 2) the efficiency appears to level off at high energy densities. It might be expected that the efficiency for irradiations which produce defects only in low-energy recoils would be nearly zero since there would be no stimulated motion. Unfortunately, 300-keV He irradiation of Pt-Si does not produce only low energy recoils; approximately 25% of the defects produced by the He irradiation result from recoils above 6-keV. Since the efficiency for the He irradiation is also ~25%, we consider the simple model that the efficiency for recoils below 6-keV is zero, and that the efficiency for recoils above 6 keV is 1. Using this simple model the efficiencies of the other irradiations can be qualitatively explained. The fraction of defects produced in recoils above 6-keV for the Ne, Ar, Kr, and Xe irradiations are 60, 75, 85, and 90% respectively. Although these percentages are not in

FIG. 2. Efficiency of ion beam mixing in Pt-Si as a function of projectile mass.

exact agreement with the mixing efficiencies, they are reasonable considering the crudeness of the model, the uncertainties in the data, and the fact that the details of the energy deposition along the track of the projectile were ignored (i.e. the recoils for the heavier particles are in close proximity to each other). For these reasons it would not be particularly illuminating to construct a better fitting efficiency function at this time. To examine the efficiency function in more detail, it would be desirable to obtain mixing data for irradiations which produce even lower energy recoils than 300-keV He irradiation. This would set the efficiency for low-energy recoils which was "guessed" to be zero here. One of the experimental problems inherent in such an approach, however, is attaining the sufficiently high damage levels necessary to measure the mixing, but without destroying the specimen by the high concentration of implanted ions. This was just possible with 300-keV He. Nevertheless, efforts in this direction are being made.

The efficiency behavior at high energy densities also requires additional investigation. The leveling off of the efficiency at high energy densities is indicated only by the 300-keV Xe irradiation. One problem with the Xe irradiation is that the projectiles have rather limited range in Pt and this may limit the mixing. We note however, that no large deviations in the mixing parameter were observed with dose, and the efficiency for 160-keV Xe is essentially no different than that for the 300-keV Xe. Leveling off of the mixing efficiency at high recoil energies was also observed for low-temperature Ar and Kr irradiation of Ni-Si diffusion couples [6]. In fact the general shape of the efficiency curve for Ni-Si is similar to that for Pt-Si [12]. These efficiency curves are reminiscent of efficiency curves for defect production [13], radiation induced segregation [14], and disordering [15]. These studies have shown that "cascade effects" become important at relatively low recoil energies, similar to those found here. Molecular dynamic computer simulations have also shown that stimulated motion of defects in cascades is important at quite low recoil energies [9,10].

The results for the mixing at higher temperatures are also listed in Table I. There is very little dependence of mixing on temperature in Pt-Si. If we assume that thermal defect motion is suppressed at 10 K, then we must conclude that radiation-enhanced diffusion is not important to the mixing in Pt-Si for temperatures below 373 K. This result is similar to that observed for Ni-Si [6] and Pd-Si [16] for which weak temperature dependences were observed.

CONCLUSION

The present experiments show that ion beam mixing does not scale directly with the deposited damage energy during an irradiation, but that it also depends on the energy density of the cascades produced by the irradiation particle. It was also found that the mixing in Pt-Si was essentially independent of temperature below 373 K. These results seem consistent with a model of ion beam mixing in which defect motion in cascades is stimulated by the agitation of the lattice during the cooling phase of the cascade. More complete information about the efficiency function at low energy and at very high energy would be very useful in evaluating the possible mechanisms of ion beam mixing.

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