Conditions for the Suppression of Void Formation During Ion-Bombardment

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CONDITIONS FOR THE SUPPRESSION OF VOID FORMATION DURING ION-BOMBARDMENT*

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In the region of ion deposition the number of interstitials is larger than the number of vacancies produced by displacement damage. As a result void formation can be suppressed. The following conditions must be satisfied for the suppression to occur: the distribution of injected ions and the distribution of displacement damage must overlap; within this region of overlap, the irradiation conditions must be such that recombination is a significant process. It is shown that void-free zones along the ion range can be produced bordering on regions with voids both behind and in front of the displacement damage peak. The suppression of void formation is particularly severe in low-energy ion bombardments.

1. INTRODUCTION

Ion bombardment has been used to study void swelling because the higher damage rates are capable of giving, in hours, displacement doses "equivalent" to years of neutron irradiations. However, the injected ions affect void formation more dramatically than originally anticipated. A review of the experimental evidence has recently been presented by Garner.[1] Brailsford and Mansur[2] found that the injected ions would reduce the void growth rate whenever recombination was a dominant process. Lee et al.[3] experimentally verified this by Ni-ion irradiation of 316 SS that had been preconditioned by neutron irradiation to a uniform void distribution. Recently, Plumton and Wolfer[4] have shown that void nucleation can be drastically suppressed by the presence of the injected ions. This implies that the region of ion deposition and peak damage should be avoided in void formation studies.

The injected ions affect void nucleation by coming to rest as interstitials without a vacancy partner. These excess interstitials are relatively few in number. Therefore, they will only be important when most of the point defects produced by displacements are recombining either at sinks or in the bulk. This recombination loss is predominant at low temperatures and for large vacancy migration energies.[2,4]

The effect of injected interstitials depends on the overlap of the displacement damage and deposited ion profiles.[4] For a high energy ion, e.g. 14 MeV, there is a large ion range so that TEM work can be done in a region midway along the range far from the influence of the front surface or the injected ions. However, as the ion energy is lowered, the mutual overlap becomes an increasing fraction of the total range, until the overlap will be large enough so that no region exists free from the influence of the surface or the injected interstitials.

2. THEORY AND RESULTS

The void nucleation theory presented previously[4] is used in this study with the modification that a surface sink term also is included. The experimental results of Garner and Thomas[5] were used to obtain the reduction in vacancy concentration due to front surface

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proximity. The experimentally determined average denuded zone width, L_{vf}, was found to depend on the vacancy diffusivity D_v and displacement rate P according to the relation

$$L_{vf} \sim \left(\frac{D_v}{P}\right)^{1/2} .$$

This denuded zone width was then used to reduce the value of C_v, the vacancy concentration, in the rate equations according to the equation

$$D_v C_v = D_v C_v \Big|_{Bulk} \left(1 - e^{-2x/L_{vf}}\right)$$

where x is the distance into the sample. This approach gave denuded zones on the same order as those observed by Garner and Thomas.[5] The materials parameters used are the same as employed previously.[4]

The calculated void nucleation rates versus depth for ion irradiated nickel are presented in Figs. 1-3 for 2.5 MeV Ni ions, in Figs. 4 and 5 for 1 MeV Ni ions, and in Fig. 6 for 0.5 MeV Ni ions. The extensive parametric study on the effect of surface denuding and injected interstitials is illustrated here by two cases, namely: case 1 for E_{vm} = 1.1 eV, E_{vf} = 1.8 eV, and Q = 1 x 10^{14} m^{-2}; and case 2 for E_{vm} = 1.2 eV, E_{vf} = 1.7 eV, and Q = 5 x 10^{13} m^{-2}. E_{vm} and E_{vf} are the vacancy migration and formation energies, respectively, while Q is the total sink strength. Figures 1, 5, and 6 are for case 1 (sink dominant regime) while Figs. 2, 3, and 4 are for case 2 (recombination dominant regime). In these figures, the void nucleation rate with excess interstitials neglected is shown by a dashed line and with excess interstitials included by a solid line.

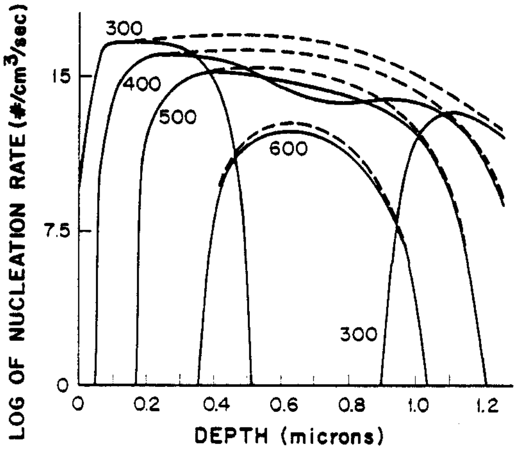

FIGURE 1
Void nucleation rate vs. depth for 2.5 MeV Ni ions incident on Ni (BRICE code, case 1).

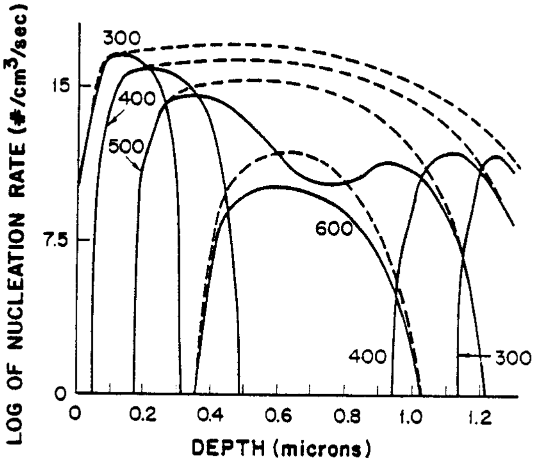

FIGURE 2
Void nucleation rate vs. depth for 2.5 MeV Ni ions incident on Ni (BRICE code, case 2).

The BRICE code[6] and HERAD code[7] were used to calculate the displacement rate and excess interstitial fraction for Figs. 1, 2, 5, and 6 and Figs. 3 and 4, respectively. For 2.5 MeV Ni ions, and higher energies, the difference between the two displacement codes is evident (Figs. 2 and 3). For energies of 1 MeV and lower, the overlap between the displacement rate profile and excess interstitial fraction profile is almost complete so that differences

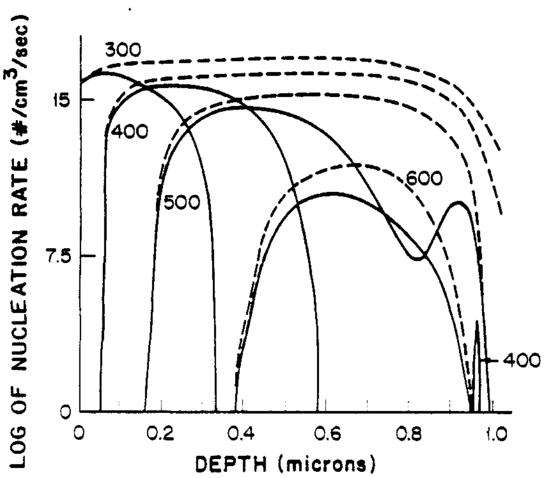

FIGURE 3
Void nucleation rate vs. depth for 2.5 MeV Ni ions incident on Ni (HERAD code, case 2).

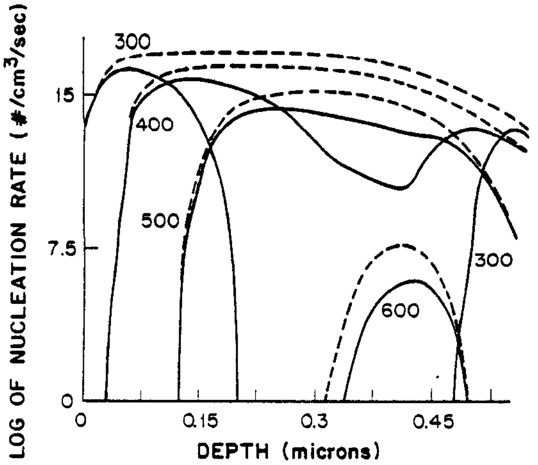

FIGURE 4
Void nucleation rate vs. depth for 1 MeV Ni ions incident on Ni (HERAD code, case 1).

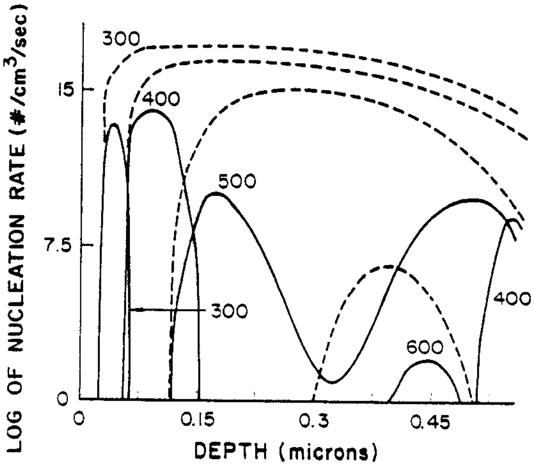

FIGURE 5
Void nucleation rate vs. depth for 1 MeV Ni ions incident on Ni (BRICE code, case 2).

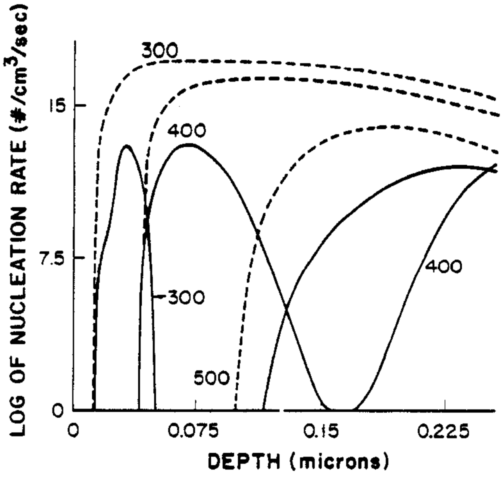

FIGURE 6
Void nucleation rate vs. depth for 0.5 MeV Ni ions incident on Ni (BRICE code, case 1).

in shapes of the profiles do not manifest themselves in the nucleation profile.

All figures illustrate the suppression of void nucleation at T = 300°C, while Fig. 1 (case 1) shows only a small decrease in the nucleation rate at 500 and 600°C. Figures 2 and 3 (case 2) both show 1-1/2 orders of magnitude decrease at 600°C (suppression values quoted at peak suppression). At 500°C Fig. 2 shows a 4-1/2 decade decrease while Fig. 3 shows almost 7 orders of magnitude decrease. Figures 2 and 3 illustrate (T = 300-500°C) the possibility of two void swelling peaks in the depth profile, one before and one after the peak of ion deposition. Figure 4 (case 1) demonstrates that as the incident ion energy is lowered, the suppression of void nucleation becomes pronounced even at high temperatures. For 1 MeV incident ions in a recombination dominated case (Fig. 5, case 2) only a band of voids nucleated just below the surface is left at low temperatures. At higher temperatures, two bands of severely suppressed void nucleation occur. For 0.5 MeV ions, the surface denuding prevents void nucleation at 600°C (Fig. 6, case 1), while the suppression is again severe and leads to two peaks at 400°C, and a reduction by 4 orders of magnitude at 500°C.

3. DISCUSSION

When void swelling after ion bombardment is measured either from step heights or by TEM in the peak damage region the effect of injected interstitials is present. The precipitous decline of void swelling towards lower temperatures as obtained by these two techniques[8] is possibly due to injected interstitials.

A void free gap or a reduction in swelling in the middle of the displacement depth profile has been observed by several authors. Whitley[9] observed a void free gap in the depth distribution at low temperature (400°C) in nickel. Johnston et al.[10] found a midrange swelling reduction at high temperatures (625°C) in stainless steel. Farrell et al.[11] also observed a midrange swelling reduction at 600°C in nickel. The existence of two bands of voids, one before and one after the peak of ion deposition, is in agreement with the results of the present study.

The degree and extent of the injected interstitial effect depend critically on the overlap of the profiles for displacement damage and deposited ions. The comparison between two codes for displacement damage shows that the HERAD code gives larger void suppressions in the peak deposition region than does the BRICE code at high temperatures. Since HERAD involves a more detailed modeling of the collision process, results derived from it are presumably more accurate.

The combined effect of surface denuding and injected interstitials can lead to a total suppression of void nucleation at all temperatures for heavy-ion bombardment with energies on the order of 0.5 MeV or less, as found in the present study. In order to compensate for this total suppression, significant amounts of inert gases must be implanted either before or during the heavy ion bombardment.

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