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APPLICATIONS OF THE THEORY OF CAVITY GROWTH TO DUAL-ION SWELLING EXPERIMENTS*

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ABSTRACT

The rate theory of cavity growth is applied to study the effects of helium gas on cavity swelling. The variation of swelling with temperature is emphasized. (1) Expressions are derived showing that the primary effect of the helium is in pressurizing cavities and that a secondary effect is in altering the microstructural sink strengths. The expressions simplify in the parameter range of engineering interest such that the temperature regime of swelling is predicted to shift upward in approximately direct proportion to the cavity gas pressure. (2) Recent experimental data on swelling of a pure stainless steel type alloy under dual-nickel and helium-ion bombardment is interpreted. Helium-free, helium-coimplanted, and helium-preimplanted swelling results can be explained by the theory. It is necessary to account for the partitioning of the helium to dislocations as well as to cavities in order to explain the experimental results for helium coimplantation. (3) Model studies for physically reasonable parameters reveal the importance of the He/dpa ratio.

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1. Introduction

Helium may be injected into a metal or alloy during irradiation as the result of reactor neutron-induced transmutation reactions, or during accelerator bombardment with the use of dual beams of helium and a more highly damaging heavy ion (e.g., Ni). The gas may encounter several fates as it diffuses through the material. It may be trapped at sinks present in irradiated microstructures such as cavities, dislocations, precipitates, and grain boundaries. It may also undergo reactions with vacancies and interstitials and higher order clusters of these defects. Since solute segregation and precipitation behavior are influenced by point defect fluxes, helium may thus affect the local alloy chemistry. In general the full effect of helium on cavity swelling or other radiation-induced changes in properties can only be understood by considering all processes of this type. However, for relatively pure materials which do not exhibit extensive second phase formation the problem is simplified considerably. When the influence of helium and its mode of introduction on the cavity number density are also known — and the number density can be measured at relatively low dose — the effects of helium on cavity growth can be examined using the rate theory of cavity growth.

The direct effect of helium in pressurizing cavities has been included in the theory of cavity growth [1]. The swelling at high temperatures is increased as a consequence of the lowering of the vacancy thermal emission rate resulting from the internal pressurization. The temperature and dose dependencies of swelling are therefore sensitive functions of the gas content and mode of introduction. The variability of swelling due to this effect under different rates of gas generation is explored in Ref. [2]. However, not all gas arrives at cavities. The effects of the partitioning of gas among

various sinks and to point defect reactions are developed in Ref. [3]. Thus in its present form the theory of cavity growth should be directly applicable to irradiation-induced swelling experiments where all these processes occur.

Recently a large amount of experimental data concerning the effects of helium on swelling has been generated. Both neutron and dual-ion swelling experiments have been conducted in a number of materials. In particular, the work of Farrell and Packan [4-6] represents an extensive matrix of temperature and gas implantation conditions during Ni ion bombardment of a "pure" stainless steel type alloy.

In the present paper the theory of cavity growth is systematically applied to interpret the results of these experiments with two objectives in mind. First, to determine whether the existing theory is capable of explaining the variety of results observed, and second, to focus on the physical bases of the important effects by analysis and parametric studies.

2. Theory

2.1 Rate Equations

The chemical rate theory has now been developed to include a wide variety of processes. For the present work the appropriate form of the theory includes the presence of gas, the effects of in-cascade recombination, cascade collapse to form vacancy loops, and the effects of the ions injected as self-interstitials by the bombarding beam. The relationships controlling point defect kinetics and evolution of microstructure are outlined below.

Point defect conservation is described by the equations

$$G_v - RC_v C_i - K_v C_v = \frac{\partial C_v}{\partial t} \quad , \quad (1)$$

$$G_i - RC_v C_i - K_i C_i = \frac{\partial C_i}{\partial t} \quad . \quad (2)$$

Here G_V and G_i are the vacancy and interstitial generation rates per unit volume.

$$G_V = Gf(1 - \epsilon_V) + G_T, \quad (3)$$

where G is the atomic displacement rate per unit volume, f is the ratio of the generation rate of defects surviving the cascade to the displacement rate and ϵ_V is the fraction of these vacancies that are retained in vacancy loops. G_T is the vacancy generation rate by thermal emission from sinks.

$$G_T = D_V C_V^e \sum_j \xi^j S_V^j, \quad (4)$$

where $D_V = D_V^0 \exp(-E_V^m/kT)$ is the vacancy diffusion coefficient, D_V^0 is a constant, E_V^m is the vacancy migration energy, k is the Boltzmann constant and T is absolute temperature. C_V^e is the bulk thermal vacancy concentration per unit volume which is, in the absence of impurity traps, given by $C_V^e = \Omega^{-1} \exp(S_V^f/k) \exp(-E_V^f/kT)$ where Ω is the atomic volume, S_V^f is the entropy of vacancy formation, and E_V^f is the energy (enthalpy) of vacancy formation. ξ^j is the ratio of thermal vacancies at sink type j to that in the bulk. For cavities of radius r_c , $\xi^c = \exp\left[\left(\frac{2\gamma}{r_c} - P\right)\Omega/kT\right]$ so that the concentration of thermal vacancies at a cavity of radius r_c is

$$C_V^e(r_c) = \Omega^{-1} \exp(S_V^f/k) \exp\left\{-\left[E_V^f - \left(\frac{2\gamma}{r_c} - P\right)\Omega\right]/kT\right\}, \quad (5)$$

where γ is the surface tension and P is the pressure of gas contained within the cavity. For dislocations, $\xi^d = 1$. For faulted dislocation loops, $\xi^l = \exp[\pm(\gamma_f + E_\ell)a^2/kT]$ where γ_f is the stacking fault energy and E_ℓ is the elastic line energy. The plus sign applies to vacancy loops while the minus sign applies to interstitial loops. Finally, S_V^j is the sink strength of sink type j for vacancies, with an analog notation for interstitials.

For cavities

$$S_{v,i}^c = 4\pi r_c N_c Z_{v,i}^c (1 + \sqrt{S_{v,i}^c} r_c) , \quad (6)$$

where N_c is the number of cavities, $Z_{v,i}^c$ are the cavity capture efficiencies, and $S_{v,i} = \sum_j S_{v,i}^j$ are the total sink strengths of all sinks for vacancies and interstitials. The sink strengths of dislocations are taken as

$$S_{v,i}^d = Z_{v,i}^d L , \quad (7)$$

where $Z_{v,i}^d$ are the capture efficiencies of dislocations for vacancies and interstitials and L is the dislocation density. The sink strengths for vacancy loops are taken as

$$S_{v,i}^{v\ell} = 2\pi Z_{v,i}^d r_{v\ell} , \quad (8)$$

where $r_{v\ell}$ is the radius of the vacancy loop. The interactive terms analogous to the last term of eq. (6) are ignored for dislocations and loops since they are smaller than those for cavities. The total sink strengths employed in later calculations are therefore

$$S_{v,i} = 4\pi r_c N_c Z_{v,i}^c (1 + \sqrt{S_{v,i}^c} r_c) + Z_{v,i}^d (L + 2\pi r_{v\ell}) . \quad (9)$$

The interstitial generation rate is given by

$$Gf(1 + \epsilon_i) , \quad (10)$$

where ϵ_i is the additional interstitial generation rate, in units of Gf , due to the self-ions injected by the bombarding beam.

In eqs. (1) and (2) $C_{v,i}$ is the vacancy, interstitial concentration per unit volume and $R = 4\pi r_0 (D_i + D_v)$ is the coefficient of recombination for interstitials and vacancies where r_0 is the radius of recombination. The $K_{v,i}$ are the loss rates of vacancies, interstitials to sinks per unit vacancy, interstitial concentration. These loss rates are simply related to the sink

strengths by $K_{v,i} = D_{v,i} S_{v,i} = D_{v,i} \sum_j S_{v,i}^j$ where the summation is over all types of sinks in the system.

The growth rate of cavities is described by

$$\frac{dr_c}{dt} = \frac{\Omega}{r_c} \left[Z_v^c D_v C_v - Z_i^c D_i C_i - Z_v^c D_v C_v^e(r_c) \right], \quad (11)$$

where t denotes time. The evolution of vacancy loops is described by

$$\frac{dq^{v\ell}}{dt} = \epsilon_v fG + D_v S_v^{v\ell} [C_v - C_v^e(r_{v\ell})] - D_i S_i^{v\ell} C_i, \quad (12)$$

and

$$\frac{dN^{v\ell}}{dt} = n^{v\ell} \left\{ 1 - (r_0 b)^{-1} \left[Z_i^{v\ell} D_i C_i - Z_v^{v\ell} D_v [C_v - C_v^e(r_{v\ell})] \right] \right\}, \quad (13)$$

where $q^{v\ell}$ is the number of vacancies in vacancy loops per unit volume, $N^{v\ell}$ is the number of vacancy loops per unit volume, $n^{v\ell}$ is the generation rate of vacancy loops per unit volume, r_0 is the initial size at which vacancy loops are produced and b is a lattice dimension. The effects of helium gas are manifest in these equations through the effect of pressure, P , in eqs. (5) and (11) and through changes in the sink strengths and therefore loss rates to sinks, the K 's of eqs. (1) and (2).

With values of parameters appearing in these equations chosen to apply to the specific experiments to be analyzed, numerical solutions for the cavity swelling as a function of temperature and gas injection rates may be obtained. Before proceeding with this work, however, it is desirable to further develop the implications of above equations.

2.2 Two Effects of Helium Gas

In the context of the above relationships, two important effects of gas on swelling occur through (1) the pressurization of cavities, and (2) the influence on the number density of cavities. The former effect is completely

described by the present theory in the sense that a change in the gas content can be precisely translated to an effect on swelling. The latter effect is included in the present theory only when the effect of a change in helium content is related to a change in cavity number density by external means. That is, it is possible to predict the effect of varying the cavity number density (or of varying the densities or strengths of other sinks) on swelling but it is not yet possible to predict accurately the number density of cavities that will be formed in response to given gas conditions. These two effects are examined below.

We are specifically interested in the effects of gas on the temperature regime of cavity swelling. The method employed is similar to that developed previously [8] to derive the temperature shift of cavity growth with changes in dose rate, changes in the primary point defect loss processes, and changes in microstructural sink strengths. Solving the steady-state forms of eqs. (1) and (2) for the C's, using eq. (9) for the sink strengths and substituting into eq. (11), it can be shown that where cavities, dislocations, and mutual recombination are the main modes of point defect loss we may write

$$\frac{dr_c}{dt} = \frac{\Omega}{r_c} \left\{ \frac{LD_i D_v}{2R} \left[(1 + \eta)^{1/2} - 1 \right] \left(z_v^c z_i^d - z_i^c z_v^d \right) - z_v^c D_v C_v^e (r_c) \right\} , \quad (14)$$

where $\eta = \frac{4RG}{D_i D_v S_i S_v}$ is a measure of (but not generally equal to) the ratio of point defects lost to recombination to those lost to sinks. Thus the growth rate is expressed as the difference between a radiation driven term and a thermal shrinkage term. When the ratio of the second term to the first term in the brackets of eq. (14) equals unity then the cavity growth rate is zero and this defines an upper cutoff temperature. If the gas pressure or sink strength (or dose rate) were changed then a new temperature could be found where this ratio would again be unity. These new conditions would define a temperature shift in the upper cutoff temperature. More generally, we may

select the ratio of the second term to the first term to be any constant A, and this value would define a specific temperature T_A . The value of A varies from zero at temperatures near the peak swelling temperature to unity at the swelling cutoff temperature. Thus the analysis here applies to temperatures above the peak swelling temperature up to the upper swelling cutoff temperature. We now require as the operational definition of temperature shift that the ratio A be retained at two different gas pressures or sink strengths. That is, we require

$$\frac{2Z_V^C D_V^C C_V^e (r_c) R}{L D_i D_V} \left\{ \left[(1 + \eta)^{1/2} - 1 \right] \left(Z_V^C Z_i^d - Z_V^d Z_i^C \right) \right\}^{-1} = A \quad (15)$$

The procedure is to equate the left-hand side of equation (15) at one set of gas pressure and sink strengths to itself at another set of gas pressure and sink strengths. The result obtained can be solved to yield

$$T_A^{(2)} - T_A^{(1)} = \frac{T_A^{(1)} \left[1 - \frac{\Gamma^{(2)}}{E_V^f} \right] \Gamma^{(1)}}{E_V^f - \Gamma^{(1)} - k T_A^{(1)} \ell \ln M} - T_A^{(1)} \frac{\Gamma^{(2)}}{E_V^f} + \frac{k T_A^{(1)2} \left(1 - \frac{\Gamma^{(2)}}{E_V^f} \right) \ell \ln M}{E_V^f - \Gamma^{(1)} - k T_A^{(1)} \ell \ln M} \quad (16)$$

where

$$M = \frac{L^{(2)} [(1 + \eta^{(2)})^{1/2} - 1]}{L^{(1)} [(1 + \eta^{(1)})^{1/2} - 1]} \quad (17)$$

Thus M contains the information on the microstructures and partitioning of point defects at the two conditions (1) and (2). The quantity $\Gamma = \left(\frac{2\gamma}{r_c} - P \right) \Omega$ (18) contains the information on the enhancement of vacancy thermal emission at cavities.

It is now possible to isolate the effects of varying gas pressure alone, and of varying microstructure alone. To find the temperature shift due to

gas pressure alone we set $M = 1$, i.e., we equate the sink strengths and the ratios of point defect loss by recombination to that at sinks under both conditions.* Equation (16) then becomes

$$T_A^{(2)} - T_A^{(1)} = \frac{T_A^{(1)} \left[1 - \frac{\Gamma^{(2)}}{E_V^f} \right] \Gamma^{(1)}}{E_V^f - \Gamma^{(1)}} - T_A^{(1)} \frac{\Gamma^{(2)}}{E_V^f} . \quad (19)$$

As shown by substituting numerical values in eq. (18) (values given below)

$\Gamma \ll E_V^f$, so that we may obtain the simple result

$$\Delta T \sim \frac{2\gamma\Omega}{r_c E_V^f} T_A^{(1)} \Delta\beta , \quad (20)$$

where $\Delta T = T_A^{(2)} - T_A^{(1)}$ and $\Delta\beta = \beta^{(2)} - \beta^{(1)}$ and β is the gas pressure in units of $\frac{2\gamma}{r_c}$, i.e.,

$$\beta = P \left(\frac{2\gamma}{r_c} \right)^{-1} . \quad (21)$$

Equation (20) shows that the shift in the temperature of cavity growth for a change in the pressure of gas contained within the cavities is approximately a direct proportion.

To obtain an estimate of the temperature shift of cavity growth with a change from $\beta = 0$ (no gas) to $\beta = 1$ (equilibrium bubble) we substitute into eq. (20) the values $\Delta\beta = 1$, $\gamma \sim 2$ joules/m², $\Omega \sim 1 \times 10^{-29}$ m³, $r_c \sim 3$ nm[†],

*It is to be emphasized that in the numerical calculations of the next section both gas pressures and sink strengths evolve.

[†]For these conditions it is found that the cavity radius at which the gas bubble to bias-driven transition takes place is 3–4 nm. Since in this gas assisted regime of cavity growth, gas is unimportant above this value, this is the physically appropriate radius to which the temperature shift applies.

$E_V^f \sim 1.6$ eV and $T_A \sim 1000$ K. The result is $\Delta T_A \sim 50^\circ\text{C}$. Thus in the experiments to be analyzed subsequently it is anticipated that an upward shift in the peak swelling temperature of about 50°C will be observed between the gas free and high gas coimplantation rate experiments.

To evaluate the temperature shift due to changes in sink strength and partitioning alone we take $\Gamma^{(2)} = \Gamma^{(1)} = 0$, i.e., we specify equilibrium bubbles in both cases. In this case eq. (16) becomes

$$T_A^{(2)} - T_A^{(1)} = \frac{\frac{kT_A^{(1)2}}{E_V^f} \ell n M}{1 - \frac{kT_A^{(1)}}{E_V^f} \ell n M} \quad (22)$$

Four limiting cases of this expression corresponding to recombination dominated ($\eta \gg 1$) or sink dominated ($\eta \ll 1$) point defect loss have been investigated: $\eta^{(1)} \gg 1, \eta^{(2)} \ll 1$; $\eta^{(1)}, \eta^{(2)} \gg 1$; $\eta^{(1)}, \eta^{(2)} \ll 1$; and $\eta^{(1)} \ll 1, \eta^{(2)} \gg 1$. In all cases it is found that the temperature shift given by eq. (22) is smaller than that given by eq. (20) in cases of practical interest (typically several-fold) and may be in the opposite sense depending on the precise ratios of sink strengths.

3. Comparison with Experimental Results

In this section the results of calculations using the theory outlined above are compared with the experimentally observed temperatures dependence of swelling at 70 dpa [6]. Figure 1 shows swelling versus temperature for helium free and helium coimplantation bombardment experiments where the ratio of the gas to displacement production rate is 20 appm He/dpa. The points represent the experimental measurements while the curves represent the calculations. Apparently the main effects of the gas are to increase the swelling temperature range by roughly 50°C and to raise the peak swelling value.

Table 1 gives the values of the parameters used in the theoretical calculations. Table 2 gives the cavity and dislocation densities used as input for the theoretical calculations. These values represent averages over several measurements from 1 to 70 dpa. Although the actual values are somewhat dose dependent they are taken as fixed for simplicity. The number densities for both the helium-free and coimplanted cases are taken as equal at the three lowest temperatures. This is because the effects of gas in the theory are unimportant at these temperatures and because the experimentally observed swelling is similar for both cases at 675°C. Although the experimentally observed swelling does differ at the two lower temperatures, these differences are not attributed to the effects of helium considered here.

The particular choices of E_V^m , G , bias, ϵ_i , and ϵ_V are important to obtaining agreement between theory and experiment. Slight variations in these quantities result in a departure of the theoretical curves from the experimental data. This point is considered in more detail later, along with the critical importance of the ratio of gas injection rate to displacement rate. However, it cannot be claimed that this combination of parameters is the unique best set. All that can be stated is that parametric studies in this region of parameter space revealed no better set. The procedure consisted of taking as fixed all the parameters of Table 1 except bias, ϵ_V , and ϵ_i . The correct values of these parameters were selected by fitting to the experimental helium-free curve.

It was then attempted to predict the swelling behavior with continuous helium coimplantation using this fixed set of parameters. Placing all the generated gas into the cavities, 20 appm He/dpa (or 10^{-7} atoms per atom He/s), results in much too high a swelling at high temperature. In order to explain the experimental results it is necessary to reduce the rate of gas introduction into cavities to ~ 0.1 appm He/dpa. A reasonable basis for this large reduction

from the injection rate has been developed in detail previously [3]. It is the partitioning of gas among the various sinks in the microstructure. To illustrate this point consider the following. It is known that dislocations are strong sinks for helium. If we take as reasonable that the ratio of sink strengths of dislocations and cavities for helium is similar to the ratio of sink strengths for point defects*, we obtain

$$Q \sim \frac{L}{4\pi r_c N_c} \quad , \quad (25)$$

for this ratio. Thus at most only Q^{-1} of the helium is partitioned to cavities, neglecting helium lost to grain boundaries and helium residing in the matrix which would reduce the fraction below Q^{-1} . However, the partitioning of gas to cavities is only important up to the critical cavity radius beyond which the cavity can grow by purely bias-driven growth. Thus the physically appropriate partitioning ratio is the value of eq. (25) integrated over time from when $r_c = 0$ to when $r_c = r_c^{\text{crit}}$. Evaluating eq. (25) at some intermediate radius, say $r_c^{\text{crit}}/2$ gives a rough estimate of the fraction of gas partitioned to cavities during this important period. Below we find that r_c^{crit} is in the range 3–4 nm. Taking the values of N_c and L from Table 2 at 750°C gives a value of Q^{-1} of order 100, i.e., of the same order of magnitude by which it was necessary to reduce the helium injection rate to explain the experimental results. Thus we find it essential to account for gas partitioning among sinks in the theory to produce physically realistic results.

We next attempted to predict the observed swelling resulting from pre-injected helium using the theory and parameters fixed by the previous analyses.

*The ratio of the sink strengths is at least proportional to the quantity given by eq. (25) for arbitrary diffusing species as shown by solving the diffusion equations for cylindrical and spherical sinks.

The effects of preinjection on cavity number density must, of course, be accounted for in the input. The main effects of preinjected helium as seen from Table 2 are to increase the number density of cavities and to create a bimodal cavity size distribution. For simplicity this bimodal cavity size distribution is modeled as a population with only two size classes, "large" and "small", whose radii represent the average of the two populations in the true distributions.

The critical radius of the large size class, i.e., that size at which a calculation can be initiated with subsequent high temperatures swelling occurring, was determined empirically. Calculations initiated with cavity sizes below this value give no cavity growth at high temperature. Since no gas is being fed into the cavities, there is, therefore, no gas assisted swelling regime. The radius of the small size class is below the critical size so that these cavities do not grow but function as recombination centers. As shown in Fig. 2 the theoretical curve agrees with the experimental data when the initial radius of the large size class is taken as approximately 4 nm but does not agree when the initial size is taken as 2 nm.

4. Parametric Dependence

Having fixed the values of the parameters appearing in the theory with the help of the experimental data it is desirable to investigate the relative effects of the several important processes for a range of parameter values. Of primary interest here is the effect of helium implanted simultaneously with displacement damage. This can be expressed conveniently in terms of the swelling response to the ratio of helium injection rate to displacement rate. Figure 3 gives the calculated swelling with temperature for the range 0 to 2 appm He/dpa injected into cavities. The injection rate of helium into the specimen is simply related to this injection rate into cavities by multiplying the cavity injection rate by the ratio of the cavity plus dislocation sink

strength to the cavity sink strength. Below $\sim 2 \times 10^{-3}$ appm He/dpa, the helium apparently has little effect on void growth. When the ratio is 2×10^{-2} , however, there is a substantial increase in the swelling at high temperatures. When the ratio is further increased by a factor of 100 there is a further substantial increase in swelling at high temperature, although the increase per helium atom is not as large as for the initial increase.

As discussed previously [2,3] the primary effect of gas for temperatures just above the upper cutoff temperature for gas-free swelling is to assist the cavity in reaching a size beyond which it can grow in response to the system bias. This has been called the gas-assisted swelling regime. Figure 4 illustrates the importance of the He/dpa ratio with respect to the dose at which the transition to bias-driven growth occurs. At 2×10^{-3} appm He/dpa (10^{-11} apa He/s) and 750°C , this transition never occurs under the conditions applicable here. At $\sim 6 \times 10^{-3}$ appm He/dpa the transition occurs at a dose near 30 dpa, beyond which the cavities grow rapidly until they become a major sink for point defects. At 2×10^{-2} appm He/dpa the transition occurs below 1 dpa. The ordinate of Fig. 4 is on a logarithmic scale so that the difference in cavity size at a given dose may be quite large for only a modest change in the gas injection rate.

A final aspect of parameter selection for these experiments should be mentioned. The ratio of the generation rate of point defects to the displacement production rate, f , has been taken equal to 0.2. That the short term annealing in a cascade removes many of the defects in addition to resulting in clustering of like defects is supported by several different types of analysis [9-11]. Defects removed by short term annealing are not available for diffusion to sinks or bulk recombination described by uniform probability in eqs. (1) and (2). Thus it is physically required to use the actual defect production rate rather than the displacement rate. The value $f = 0.2$ is

typical of the magnitude of reduction common to several of the analyses mentioned above. However, the precise choice must await more detailed verification.

5. Summary

The effects of helium on swelling in the rate theory applied here are to assist high temperature swelling by cavity pressurization and to change the microstructural sink strengths. It has been shown analytically that the pressurization effect may give rise to a substantial increase in cavity growth at high temperatures. The analysis describes placing a test cavity, containing gas pressure P_1 , which may be zero, into the material and reporting its growth rate as a function of temperature. Next a cavity containing pressure, $P_2 > P_1$, is inserted into the material and its growth rate as a function of temperature is reported. In the parameter range of experimental interest the upward shift in temperature regime of swelling, ΔT , is approximately directly proportional to the increase in pressure in the cavities caused by gas, $\Delta P = P_2 - P_1$. This result is contained in eq. (20). Changes in sink strength by the introduction of helium have also been found to give rise to a lesser change in the temperature dependence of swelling.

Experimental results from dual-ion swelling experiments have been analyzed. The results of the case for gas-free bombardment are first fit using the rate theory in order to obtain the applicable parameters. With these parameters fixed, the theory is then applied to predict the results of helium coimplantation and preimplantation experiments. In order to explain the observed coimplantation results it is essential to account for the partitioning of helium between cavities and dislocations. The preimplanted results can also be explained by the theory when two size classes of cavities (as observed experimentally) are included. The smaller cavities function mainly as sinks to absorb defects of both types, thus serving primarily as recombination centers. The large size

class grows and produces the measured level of swelling provided the initial radius at the beginning of the calculations is above the critical size.

Studies of predicted results in a physically reasonable range of parameters have been made. The cavity volume is quite sensitive in these calculations to the He/apa ratio.

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Table 1

z_i^d	1.0275
z_v^j	1
z_i^c, z_v^c	1
G	6×10^{-3} dpa/s
ϵ_i	6×10^{-4}
ϵ_v	1.25×10^{-2}
f	0.2
E_i^m	0.2 eV
E_v^m	1.3 eV
E_v^f	1.6 eV
S_v^f	0
D_i^0	10^{-7} m ² /s
D_v^0	6×10^{-5} m ² /s
γ	2 joules/m ²

Table 2

T (°C)	N _v			L		
	a	b	c	a	b	c
565	2.0×10^{21}	2.0×10^{21}	1.7×10^{21} (L) 1.9×10^{22} (S)	7.5×10^{14}	7.5×10^{14}	7.4×10^{14}
625	1.1×10^{21}	1.1×10^{21}	4.4×10^{20} (L) 1.5×10^{22} (S)	3.8×10^{14}	3.8×10^{14}	3.3×10^{14}
675	2.2×10^{20}	2.2×10^{20}	1.4×10^{21} (L) 1.8×10^{21} (S)	1.0×10^{14}	1.0×10^{14}	1.1×10^{14}
750	6.5×10^{19}	3.0×10^{18}	6.0×10^{20} (L) 1.0×10^{21} (S)	9.0×10^{13}	5.0×10^{13}	9.0×10^{13}
825	4.0×10^{19}	none	none none (L) (S)	3.5×10^{13}	3.0×10^{13}	3.0×10^{13}

a = continuous helium injection

b = no gas

c = cold preinjection

(L) = large void population

(S) = small void population

Figure Captions

1. The temperature dependence of swelling for helium-free and helium-coimplanted conditions at 70 dpa. The points denote experimental measurements; $\circ$ helium-free, Δ helium-coimplanted.
2. The temperature dependence of swelling for helium coimplanted condition at 70 dpa. The point represents experimental measurements. The curves are the results of the theoretical calculation using two different values of the large size class initial cavity radius, r_c^0 .
3. Calculated variations of swelling with temperature for different helium injection rate to displacement rate ratios. All helium in these calculations is injected into cavities.
4. Calculated dose dependence of cavity size for helium coimplantation at several rates. All helium in these calculations is injected into cavities.

fig. 1
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Fig. 2
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Fig. 3
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