DIRECT OBSERVATION OF THE VACANCY STRUCTURE OF DEPLETED ZONES IN
TUNGSTEN ION IRRADIATED AT 10 K

by

Ching-Yeu Wei and David N. Seidman

Cornell University
Ithaca, New York 14853

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

December 1978

MASTER

Report #4022

Issued by

The Materials Science Center

Prepared for

THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT
No. EY-76-S-02-3158.*000

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *EB*

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DIRECT OBSERVATION OF THE VACANCY STRUCTURE OF DEPLETED ZONES
IN TUNGSTEN ION IRRADIATED AT 10 K[†]

by

Ching-Yeu Wei^{*} and David N. Seidman

Department of Materials Science and Engineering
and the Materials Science Center,
Cornell University, Bard Hall,
Ithaca, New York 14853.

ABSTRACT

The structure of depleted zones (DZs) created by the in-situ irradiation of tungsten specimens, at 10 K, with 30 keV W⁺, Mo⁺ or Cr⁺ ions has been studied by field-ion microscopy. As the mass of the 30 keV ion was decreased the following observations were made: (1) the spatial extent of the DZs increased; (2) the vacancy concentration within the DZs decreased; (3) the fraction of isolated mono-vacancies increased; and (4) subcascades formed within the DZs.

PACS index categories: 61.16.Fk; 61.80.Jh; and 61.70.Bv.

The field-ion microscope (FIM) is the only microscope that can, at present, provide us with a direct-lattice image of the primary state of radiation damage; i.e., the 3-dimensional spatial-distribution of the point defects produced by one energetic primary knocked-on atom. In this paper we present the results of a systematic and quantitative FIM study of the vacancy structure of depleted zones (DZs) in tungsten (W) specimens which had been irradiated in-situ with 30 keV W^+ , Mo^+ or Cr^+ ions at 10 K. The work reported here represents a major extension of our earlier research on W^+ ion-irradiated W at 18 and 473 K.⁽¹⁻³⁾

The FIM work on the structure of DZs in W is complementary to the many transmission electron microscope (TEM) studies on this same subject,⁽⁴⁻⁶⁾ in that the TEM observations are of that portion of the point-defect population which exists in the form of vacancy or self-interstitial atom (SIA) dislocation-loops. Whereas, employing the FIM technique, it is possible to observe both dislocation loops and the unprecipitated point-defects. This capability is particularly important for the bcc metals where the yield factor (Y) is often $\ll 1$.⁽³⁻⁶⁾ In the case of W both TEM⁽⁷⁾ and combined FIM-TEM⁽⁸⁾ studies have shown that Y is ≈ 0.1 . Thus for W approximately 90% of the point defects are in a form that is not detected by standard TEM techniques. In addition the TEM study of Ruault et al.⁽⁹⁾ indicated that the point-defect structure of the DZs determines the nature (vacancy or SIA) of the collapsed clusters observed in several fcc metals.

FIM specimens were prepared from 4-pass zone-refined single-crystal rods of W. The FIM specimens were then electropolished to a tip radius of $\approx 100 \text{ \AA}$. Next they were blunted to an average radius of 200 to 400 $\text{\AA}$, by the pulse field-evaporation technique, at 10 K in the FIM; this step produced an atomically perfect low-temperature end-form. Each FIM specimen was then irradiated in-situ at 10 K at $\leq 2 \times 10^{-9}$ Torr, in the absence of the imaging electric-field and imaging gas, to a fluence of $(2 \text{ to } 10) \times 10^{12} \text{ ion cm}^{-2}$. The flux at the specimen was $\approx 10^{11} \text{ ion cm}^{-2} \text{ sec}^{-1}$; at this flux level the time to form an adsorbed monolayer was always greater than the

time required to obtain the desired fluence. After the in-situ 10 K irradiation each specimen was re-imaged at 10 K, employing $\sim 10^{-4}$ Torr He^4 , and then dissected employing the pulse field-evaporation technique. An FIM image was recorded on 35 mm film, employing a ciné camera, after the collapse of each field-evaporation pulse; the pulse height and its duration were adjusted so that 1 atom, on the average, was removed per pulse on the (222) plane.

The thousands of feet of 35 mm ciné film recorded were analyzed employing a motion analyzer which was equipped with x-y cross-hairs and a position readout; the motion analyzer was interfaced to an x-y point plotter. This latter feature was found to be essential for reconstructing the 3-dimensional structure of a DZ from the 2-dimensional arrangement of point-defects found in each lattice plane. The details of the reconstruction procedure can be found elsewhere.⁽¹⁰⁾ The end product of our reconstruction was an isometric drawing of the arrangement of vacancies in each DZ; each drawing was generated employing the OR TEP program.⁽¹¹⁾ The results on the spatial distribution of immobile SIAs detected will be published elsewhere.

We now present the principle results concerning the spatial distribution of vacancies detected within the DZs; the fluence was such that each DZ that we detected and analyzed was produced by a single incident metal ion. A total of 11 different DZs were analyzed; 5 that were produced by 30 keV W^+ ions, 4 that were produced by 30 keV Mo^+ ions, and 2 that were produced by 30 keV Cr^+ ions; the corresponding values of the reduced-energy parameter (ϵ) in the LSS theory⁽¹²⁾ are 1.5×10^{-2} , 3.8×10^{-2} and 8.4×10^{-2} respectively. The physical quantities measured for each DZ were: (1) the number of vacancies; (2) the dimensions; (3) the vacancy concentration; (4) the distribution of 1st-nearest neighbor vacancy-clusters; and (5) the radial-distribution function (RDF) for the vacancies out to 9th-nearest neighbor.

Figure 1 exhibits 3 different DZs which were produced by 30 keV W^+ , Mo^+ or Cr^+ ions. Each open circle represents 1 vacancy and the rod connecting 2 vacancies is

equal to the 1st-nearest neighbor distance in W ($\approx 1.87 \text{ \AA}$); the perfect lattice has been omitted for clarity. The magnification factor for each of the 3 DZs is approximately the same; thus Fig. 1 gives an excellent qualitative picture as to how the spatial distribution of vacancies changes as the mass of the incident projectile (M_p) was changed from 183.86 to 52.01 amu at approximately constant damage energy. It can be seen immediately that as M_p was decreased: (1) the spatial extent of the DZ increased; (2) the vacancy concentration (number of vacancies per cm^3) decreased; (3) the number of isolated monovacancies increased and therefore the number of large 1st-nearest neighbor vacancy clusters decreased; and (4) there was a tendency to form subcascades within the DZ — this was particularly apparent in the case of the 30 keV Mo^+ DZ which consists of two distinct subcascades.

Figure 2 shows a plot of the number of vacancies, produced by single 30 keV ions, as a function of M_p for all of the 11 DZs analyzed. The solid lines were calculated from the modified Kinchin-Pease equation

$$\langle v \rangle = \frac{\kappa \langle E_o - \hat{Q} \rangle}{2E_d},$$

where $\langle v \rangle$ is the average number of point defects (either vacancies or SIAs) produced, κ is the displacement efficiency which is equal to 0.8 according to both computer simulations⁽¹³⁾ and analytical calculations,⁽¹⁴⁾ E_o the energy of the incident projectile, and E_d a displacement threshold-energy. The values of the total inelastic energy loss ($\hat{Q}$) for 30 keV W^+ , Mo^+ and Cr^+ were calculated for the Ta^+ on Ta, Ag^+ on Au and Al^+ on Zr combinations.⁽¹⁵⁾ Thus the curvature of each solid line is determined solely by the variation of $\hat{Q}$ with M_p ; it is clear that for $E_o = 30 \text{ keV}$ and the M_p s employed that $\langle v \rangle$ is not a strong function of $\hat{Q}$. The solid lines were calculated for $E_d = 42, 50$ and 60 eV ; $E_d = 42 \text{ eV}$ corresponds to the minimum measured E_d , which is for the $\langle 100 \rangle$ type directions.⁽¹⁶⁾ The existing data show that a value of E_d of ≈ 50 to 60 eV is required to explain the measured $\langle v \rangle$ s; further experiments are in progress to establish this point with greater statistical significance. The observed spread

in the value of $\langle v \rangle$ per DZ for each M_p was due to the statistical nature of the energy loss mechanisms, which resulted in an elastically-deposited energy versus distance distribution that was skewed from a Gaussian distribution. (15,17)

The average measured diameters of the DZs created by the 30 keV W^+ , Mo^+ or Cr^+ ions were 18, 25 and 42 Å respectively. The "expected" diameter of a depleted zone was taken, to first order, to be given by $2\langle y^2 \rangle^{1/2}$, where $\langle y^2 \rangle^{1/2}$ is the 2nd moment of the transverse elastically-deposited energy versus distance distribution. (17) When the values of $2\langle y^2 \rangle^{1/2}$ were multiplied by the so-called contraction factor, (18) the agreement between experiment and theory was reasonable. The vacancy concentration in each DZ was calculated by dividing the measured $\langle v \rangle$ s by the DZ volume; the DZ volume was an irregularly shaped one that enclosed all the vacancies. The following average values for the 30 keV W^+ , Mo^+ or Cr^+ DZs were obtained: 21, 10 and 4 at.%. A detailed analysis of the distribution of 1st-nearest neighbor vacancy clusters showed that the average fraction of monovacancies was 0.13, 0.19 and 0.28 in the 30 keV W^+ , Mo^+ or Cr^+ DZs respectively; and the average fraction of vacancies in 1st-nearest neighbor clusters of size 6 or greater was 0.83, 0.70 and 0.54 in the 30 keV W^+ , Mo^+ or Cr^+ DZs respectively.

The RDF was defined to be the average number of vacancies at the i th-nearest neighbor distance (r_i) measured from any vacancy. The RDF is given by

$$R(i) = \frac{1}{N_t} \sum_{j=1}^{N_t} A(i,j) ,$$

where $A(i,j)$ is the number of vacancies at r_i measured from the j th vacancy and N_t is the total number of vacancies in the DZ. Figure 3 exhibits a plot of $R(i)/Z(i)$ versus r_i in Å for the 3 DZs shown in Fig. 1; the quantity $Z(i)$ is the coordination number at the i th-nearest neighbor distance in an infinite crystal. The slope of the $R(i)/Z(i)$ vs r_i plot decreases as M_p was decreased at a constant ($E_0 - \hat{Q}$); this was a reflection of the decrease in the fraction of vacancies contained in clusters within the DZ. The quantity $R(i)/Z(i)$ should approach a small constant value, which is

independent of r_i , for the case of vacancies distributed randomly throughout a large crystal; e.g., this would be the situation obtained in a crystal that had been irradiated with electrons that had transferred an energy that was close to the minimum E_d .

The information reported here represents the most quantitative data obtained, to date, on the vacancy structure of DZs.

ACKNOWLEDGEMENTS

We wish to thank Mr. K. McCarthy, Mrs. K. Pratt and Mr. R. Whitmarsh for technical assistance and Dr. M.I. Current for useful discussions.

† Research supported by the U.S. Department of Energy. Additional support was received from the National Science Foundation through the use of the technical facilities of the Materials Science Center at Cornell University.

* Now at the General Electric Corporate Research and Development Laboratory, Schenectady, N.Y. 12301.

REFERENCES

1. L. A. Beavan, R.M. Scanlan and D.N. Seidman, Acta Met. 19, 1339 (1971).
2. K.L. Wilson and D.N. Seidman in Nuclear Metallurgy, Proc. Inter. Conf. on Defects and Defect Clusters in B.C.C. Metals and Their Alloys, edited by R.J. Arsenault (Univ. of Maryland, College Park, MD, 1973), Vol. 18, pp. 216-239.
3. D.N. Seidman, in Radiation Damage in Metals, edited by N.L. Peterson and S.D. Harkness (American Society for Metals, Metals Park, OH, 1976), pp. 28-57.
4. B.L. Eyre, J. Phys. F: Metal Phys. 3, 422 (1973).
5. M. Wilkens in Fund. Aspects of Radiation Damage in Metals, edited by M.T. Robinson and F.W. Young, Jr. (ERDA CONF-751006-P2, U.S. Dept. of Commerce, Springfield, VA, 1975), pp. 98-119.
6. K.L. Merkle in Radiation Damage in Metals, edited by N.L. Peterson and S.D. Harkness (American Society for Metals, Metals Park, OH, 1976), pp. 58-94.
7. F. Häusermann, Philos. Mag. 25, 561 and 583 (1972).
8. J.T. Buswell, Philos. Mag. 22, 391 and 787 (1970).
9. M.O. Ruault, J. Chaumont, H. Bernas and P. Sigmund, Phys. Rev. Lett. 36, 1148 (1976).
10. C.-Y. Wei and D.N. Seidman, Philos. Mag. A37, 257 (1978).
11. C.K. Johnson, Oak Ridge National Lab. Report No. 3794 plus revisions (1965 and 1970).
12. J. Linhard, M. Scharff and H.E. Schiøtt, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 33, No. 14 (1963).
13. D.K. Holmes and M.T. Robinson, in Atomic Collisions in Solids, edited by S. Datz, B.R. Appelton and C.D. Moak (Plenum, New York City, 1974), Vol. 1, p. 225.

14. P. Sigmund, Radiat. Eff. 1, 15 (1969).
15. K.B. Winterbon, Ion Implantation Range and Energy Deposition Distributions (Plenum, New York City, 1975).
16. F. Maury, M. Biget, P. Vajda, A. Lucasson and P. Lucasson, Radiat. Eff. 38, 53 (1978).
17. K.B. Winterbon, P. Sigmund and J.B. Sanders, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 37, 14 (1970).
18. P. Sigmund, G.P. Scheidler and G. Roth, in Proc. Int. Conf. Solid-State Physics Research with Accelerators, Brookhaven National Lab: Report 50083, 374 (1968).

FIGURE CAPTIONS

Fig. 1. Isometric drawings of the arrangement of vacancies within 3 different DZs.

Fig. 2. The experimental values of the number of vacancies produced by a single 30 keV ion as a function of M_p . The solid lines were calculated from a modified Kinchin-Pease equation for the indicated E_d .

Fig. 3. Normalized RDFs for the 3 DZs shown in Fig. 1.

Fig. 1

Fig. 2

Fig. 3

The field-ion microscope (FIM) is the only microscope that can, at present, provide us with a direct-lattice image of the primary state of radiation damage; i.e., the 3-dimensional spatial-distribution of the point defects produced by one energetic primary knocked-on atom. In this paper we present the results of a systematic and quantitative FIM study of the vacancy structure of depleted zones (DZs) in tungsten (W) specimens which had been irradiated in-situ with 30 keV W^+ , Mo^+ or Cr^+ ions at 10 K. The work reported here represents a major extension of our earlier research on W^+ ion-irradiated W at 18 and 473 K.⁽¹⁻³⁾

The FIM work on the structure of DZs in W is complementary to the many transmission electron microscope (TEM) studies on this same subject,⁽⁴⁻⁶⁾ in that the TEM observations are of that portion of the point-defect population which exists in the form of vacancy or self-interstitial atom (SIA) dislocation-loops. Whereas, employing the FIM technique, it is possible to observe both dislocation loops and the unprecipitated point-defects. This capability is particularly important for the bcc metals where the yield factor (Y) is often $\ll 1$.⁽³⁻⁶⁾ In the case of W both TEM⁽⁷⁾ and combined FIM-TEM⁽⁸⁾ studies have shown that Y is ≈ 0.1 . Thus for W approximately 90% of the point defects are in a form that is not detected by standard TEM techniques. In addition the TEM study of Ruault et al.⁽⁹⁾ indicated that the point-defect structure of the DZs determines the nature (vacancy or SIA) of the collapsed clusters observed in several fcc metals.

FIM specimens were prepared from 4-pass zone-refined single-crystal rods of W. The FIM specimens were then electropolished to a tip radius of $\approx 100 \text{ \AA}$. Next they were blunted to an average radius of 200 to 400 $\text{\AA}$, by the pulse field-evaporation technique, at 10 K in the FIM; this step produced an atomically perfect low-temperature end-form. Each FIM specimen was then irradiated in-situ at 10 K at $\leq 2 \times 10^{-9}$ Torr, in the absence of the imaging electric-field and imaging gas, to a fluence of $(2 \text{ to } 10) \times 10^{12} \text{ ion cm}^{-2}$. The flux at the specimen was $\approx 10^{11} \text{ ion cm}^{-2} \text{ sec}^{-1}$; at this flux level the time to form an adsorbed monolayer was always greater than the

time required to obtain the desired fluence. After the in-situ 10 K irradiation each specimen was re-imaged at 10 K, employing $\approx 10^{-4}$ Torr He^4 , and then dissected employing the pulse field-evaporation technique. An FIM image was recorded on 35 mm film, employing a ciné camera, after the collapse of each field-evaporation pulse; the pulse height and its duration were adjusted so that 1 atom, on the average, was removed per pulse on the (222) plane.

The thousands of feet of 35 mm ciné film recorded were analyzed employing a motion analyzer which was equipped with x-y cross-hairs and a position readout; the motion analyzer was interfaced to an x-y point plotter. This latter feature was found to be essential for reconstructing the 3-dimensional structure of a DZ from the 2-dimensional arrangement of point-defects found in each lattice plane. The details of the reconstruction procedure can be found elsewhere.⁽¹⁰⁾ The end product of our reconstruction was an isometric drawing of the arrangement of vacancies in each DZ; each drawing was generated employing the OR TEP program.⁽¹¹⁾ The results on the spatial distribution of immobile SIAs detected will be published elsewhere.

We now present the principle results concerning the spatial distribution of vacancies detected within the DZs; the fluence was such that each DZ that we detected and analyzed was produced by a single incident metal ion. A total of 11 different DZs were analyzed; 5 that were produced by 30 keV W^+ ions, 4 that were produced by 30 keV Mo^+ ions, and 2 that were produced by 30 keV Cr^+ ions; the corresponding values of the reduced-energy parameter (ϵ) in the LSS theory⁽¹²⁾ are 1.5×10^{-2} , 3.8×10^{-2} and 8.4×10^{-2} respectively. The physical quantities measured for each DZ were: (1) the number of vacancies; (2) the dimensions; (3) the vacancy concentration; (4) the distribution of 1st-nearest neighbor vacancy-clusters; and (5) the radial-distribution function (RDF) for the vacancies out to 9th-nearest neighbor.

Figure 1 exhibits 3 different DZs which were produced by 30 keV W^+ , Mo^+ or Cr^+ ions. Each open circle represents 1 vacancy and the rod connecting 2 vacancies is

equal to the 1st-nearest neighbor distance in W ($\approx 1.87 \text{ \AA}$); the perfect lattice has been omitted for clarity. The magnification factor for each of the 3 DZs is approximately the same; thus Fig. 1 gives an excellent qualitative picture as to how the spatial distribution of vacancies changes as the mass of the incident projectile (M_p) was changed from 183.86 to 52.01 amu at approximately constant damage energy. It can be seen immediately that as M_p was decreased: (1) the spatial extent of the DZ increased; (2) the vacancy concentration (number of vacancies per cm^3) decreased; (3) the number of isolated monovacancies increased and therefore the number of large 1st-nearest neighbor vacancy clusters decreased; and (4) there was a tendency to form subcascades within the DZ — this was particularly apparent in the case of the 30 keV Mo^+ DZ which consists of two distinct subcascades.

Figure 2 shows a plot of the number of vacancies, produced by single 30 keV ions, as a function of M_p for all of the 11 DZs analyzed. The solid lines were calculated from the modified Kinchin-Pease equation

$$\langle v \rangle = \frac{\kappa \langle E_0 - \hat{Q} \rangle}{2E_d},$$

where $\langle v \rangle$ is the average number of point defects (either vacancies or SIAs) produced, κ is the displacement efficiency which is equal to 0.8 according to both computer simulations⁽¹³⁾ and analytical calculations,⁽¹⁴⁾ E_0 the energy of the incident projectile, and E_d a displacement threshold-energy. The values of the total inelastic energy loss ($\hat{Q}$) for 30 keV W^+ , Mo^+ and Cr^+ were calculated for the Ta^+ on Ta, Ag^+ on Au and Al^+ on Zr combinations.⁽¹⁵⁾ Thus the curvature of each solid line is determined solely by the variation of $\hat{Q}$ with M_p ; it is clear that for $E_0 = 30 \text{ keV}$ and the M_p s employed that $\langle v \rangle$ is not a strong function of $\hat{Q}$. The solid lines were calculated for $E_d = 42, 50$ and 60 eV ; $E_d = 42 \text{ eV}$ corresponds to the minimum measured E_d , which is for the $\langle 100 \rangle$ type directions.⁽¹⁶⁾ The existing data show that a value of E_d of ≈ 50 to 60 eV is required to explain the measured $\langle v \rangle$ s; further experiments are in progress to establish this point with greater statistical significance. The observed spread

in the value of $\langle v \rangle$ per DZ for each M_p was due to the statistical nature of the energy loss mechanisms, which resulted in an elastically-deposited energy versus distance distribution that was skewed from a Gaussian distribution.^(15,17)

The average measured diameters of the DZs created by the 30 keV W^+ , Mo^+ or Cr^+ ions were 18, 25 and 42 Å respectively. The "expected" diameter of a depleted zone was taken, to first order, to be given by $2\langle y^2 \rangle^{1/2}$, where $\langle y^2 \rangle^{1/2}$ is the 2nd moment of the transverse elastically-deposited energy versus distance distribution.⁽¹⁷⁾ When the values of $2\langle y^2 \rangle^{1/2}$ were multiplied by the so-called contraction factor,⁽¹⁸⁾ the agreement between experiment and theory was reasonable. The vacancy concentration in each DZ was calculated by dividing the measured $\langle v \rangle$ s by the DZ volume; the DZ volume was an irregularly shaped one that enclosed all the vacancies. The following average values for the 30 keV W^+ , Mo^+ or Cr^+ DZs were obtained: 21, 10 and 4 at.%. A detailed analysis of the distribution of 1st-nearest neighbor vacancy clusters showed that the average fraction of monovacancies was 0.13, 0.19 and 0.28 in the 30 keV W^+ , Mo^+ or Cr^+ DZs respectively; and the average fraction of vacancies in 1st-nearest neighbor clusters of size 6 or greater was 0.83, 0.70 and 0.54 in the 30 keV W^+ , Mo^+ or Cr^+ DZs respectively.

The RDF was defined to be the average number of vacancies at the i th-nearest neighbor distance (r_i) measured from any vacancy. The RDF is given by

$$R(i) = \frac{1}{N_t} \sum_{j=1}^{N_t} A(i,j) \quad ,$$

where $A(i,j)$ is the number of vacancies at r_i measured from the j th vacancy and N_t is the total number of vacancies in the DZ. Figure 3 exhibits a plot of $R(i)/Z(i)$ versus r_i in Å for the 3 DZs shown in Fig. 1; the quantity $Z(i)$ is the coordination number at the i th-nearest neighbor distance in an infinite crystal. The slope of the $R(i)/Z(i)$ vs r_i plot decreases as M_p was decreased at a constant $(E_0 - \hat{Q})$; this was a reflection of the decrease in the fraction of vacancies contained in clusters within the DZ. The quantity $R(i)/Z(i)$ should approach a small constant value, which is

independent of r_i , for the case of vacancies distributed randomly throughout a large crystal; e.g., this would be the situation obtained in a crystal that had been irradiated with electrons that had transferred an energy that was close to the minimum E_d .

The information reported here represents the most quantitative data obtained, to date, on the vacancy structure of DZs.

ACKNOWLEDGEMENTS

We wish to thank Mr. K. McCarthy, Mrs. K. Pratt and Mr. R. Whitmarsh for technical assistance and Dr. M.I. Current for useful discussions.

† Research supported by the U.S. Department of Energy. Additional support was received from the National Science Foundation through the use of the technical facilities of the Materials Science Center at Cornell University.

* Now at the General Electric Corporate Research and Development Laboratory, Schenectady, N.Y. 12301.

REFERENCES

1. L. A. Beavan, R.M. Scanlan and D.N. Seidman, Acta Met. 19, 1339 (1971).
2. K.L. Wilson and D.N. Seidman in Nuclear Metallurgy, Proc. Inter. Conf. on Defects and Defect Clusters in B.C.C. Metals and Their Alloys, edited by R.J. Arsenault (Univ. of Maryland, College Park, MD, 1973), Vol. 18, pp. 216-239.
3. D.N. Seidman, in Radiation Damage in Metals, edited by N.L. Peterson and S.D. Harkness (American Society for Metals, Metals Park, OH, 1976), pp. 28-57.
4. B.L. Eyre, J. Phys. F: Metal Phys. 3, 422 (1973).
5. M. Wilkens in Fund. Aspects of Radiation Damage in Metals, edited by M.T. Robinson and F.W. Young, Jr. (ERDA CONF-751006-P2, U.S. Dept. of Commerce, Springfield, VA, 1975), pp. 98-119.
6. K.L. Merkle in Radiation Damage in Metals, edited by N.L. Peterson and S.D. Harkness (American Society for Metals, Metals Park, OH, 1976), pp. 58-94.
7. F. Häusermann, Philos. Mag. 25, 561 and 583 (1972).
8. J.T. Buswell, Philos. Mag. 22, 391 and 787 (1970).
9. M.O. Ruault, J. Chaumont, H. Bernas and P. Sigmund, Phys. Rev. Lett. 36, 1148 (1976).
10. C.-Y. Wei and D.N. Seidman, Philos. Mag. A37, 257 (1978).
11. C.K. Johnson, Oak Ridge National Lab. Report No. 3794 plus revisions (1965 and 1970).
12. J. Linhard, M. Scharff and H.E. Schiøtt, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 33, No. 14 (1963).
13. D.K. Holmes and M.T. Robinson, in Atomic Collisions in Solids, edited by S. Datz, B.R. Appelton and C.D. Moak (Plenum, New York City, 1974), Vol. 1, p. 225.

14. P. Sigmund, Radiat. Eff. 1, 15 (1969).
15. K.B. Winterbon, Ion Implantation Range and Energy Deposition Distributions (Plenum, New York City, 1975).
16. F. Maury, M. Biget, P. Vajda, A. Lucasson and P. Lucasson, Radiat. Eff. 38, 53 (1978).
17. K.B. Winterbon, P. Sigmund and J.B. Sanders, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 37, 14 (1970).
18. P. Sigmund, G.P. Scheidler and G. Roth, in Proc. Int. Conf. Solid-State Physics Research with Accelerators, Brookhaven National Lab: Report 50083, 374 (1968).

FIGURE CAPTIONS

Fig. 1. Isometric drawings of the arrangement of vacancies within 3 different DZs.

Fig. 2. The experimental values of the number of vacancies produced by a single 30 keV ion as a function of M_p . The solid lines were calculated from a modified Kinchin-Pease equation for the indicated E_d .

Fig. 3. Normalized RDFs for the 3 DZs shown in Fig. 1.

Fig. 1

Fig. 2

Fig. 3