

TEMPERATURE DEPENDENCE OF THE VACANCY SINK EFFICIENCY
OF STACKING FAULT TETRAHEDRA IN QUENCHED GOLD

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ABSTRACT

The average efficiency of stacking fault tetrahedra as vacancy sinks in quenched gold has been measured over the annealing temperature range from 20°C to 100°C. An electron metallographic technique (Siegel et al. 1968) was used for these measurements in which the competition between growing tetrahedra and a free surface for the annihilation of migrating supersaturated vacancies in quenched samples was studied. The measured sink efficiency, $\bar{\epsilon}$, varied from 0.5 ± 0.1 at 20°C to 0.9 ± 0.1 at 100°C. Using these results and the previous measurements of $\bar{\epsilon}$ at 60°C a plot of $\ln \bar{\epsilon}$ versus $1/kT$ was found to be linear with a slope of -0.07 eV. The significance of the observed temperature dependence is discussed in terms of the jog-line (ledge) migration model for the growth of stacking fault tetrahedra. It is concluded that the climb process leading to tetrahedron growth is thermally activated with an effective activation energy of 0.07 eV. The results are discussed in terms of the relationship between $\bar{\epsilon}$ and investigations of the annealing of vacancy defects in quenched gold.

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1. INTRODUCTION

Stacking fault tetrahedra, which form by the precipitation of supersaturated vacancy defects, most likely grow by the nucleation and subsequent vacancy induced migration of jog lines or ledges across their faces. The growth of tetrahedra by such a mechanism was suggested by de Jong and Koehler (1963a) and has been considered further by Kuhlmann-Wilsdorf (1965).

Vacancy annihilation at stacking fault tetrahedra leading to their growth has been experimentally investigated in detail in quenched gold (Siegel 1966a, b). It was shown that the vacancy annealing rate varied with the density and size of the tetrahedron sinks. Further, it was found that the average vacancy sink efficiency, $\bar{\epsilon}$, (which may be defined as the ratio of the actual annihilation rate at a sink to that at a sink which maintains the vacancy concentration at its equilibrium value over its entire surface) of the tetrahedra was not unity as had been tacitly assumed in earlier work. By comparison with the vacancy annealing rates to black spot defects, a sink efficiency was determined for the tetrahedra which was ~ 0.1 at 60°C for vacancy concentrations in the range $0.67 \times 10^{-5} \leq c_v \leq 1.11 \times 10^{-5}$.

Subsequently, two direct measurements were made of the average value of $\bar{\epsilon}$ at 60°C for tetrahedra in quenched gold using an electron metallographic sectioning technique (Siegel *et al.* 1968) and stereo electron microscopy (Siegel *et al.* 1969). The $\bar{\epsilon}$ obtained were essentially averaged over the major period of tetrahedron growth (i.e., for varying vacancy supersaturation) and values of approximately 0.6 and 0.7 were found for initial vacancy concentrations of 1.1×10^{-4} and 2.0×10^{-4} ,

respectively. A comparison of these results with the previous sink efficiency information implies that $\bar{\epsilon}$ increases with increasing vacancy supersaturation.

In order to clearly understand observed vacancy annealing kinetics in quenched metals, and to thereby obtain such defect parameters as activation energies for vacancy defect migration, it is necessary to obtain a detailed knowledge of the various parameters which enter into the appropriate diffusion equation. It has been pointed out (Balluffi and Siegel 1965) that for the annealing of simple defects to a distribution of fixed sinks at a density of N_s and with average effective radius \bar{b} , the instantaneous annealing rate may be given by

$$\frac{d\bar{c}}{dt} = - 4\pi \bar{b} N_s \bar{c} D_{OV} \exp (-E_V^m/kT) ,$$

where \bar{c} is the average fractional concentration of excess mobile defects with an activation energy for migration of E_V^m , and D_{OV} is the temperature independent part of the vacancy defect diffusion coefficient. For the case of stacking fault tetrahedra the effective sink radius can be written as $\bar{b} = \bar{\epsilon} (L_{RMS}/2)$, where L_{RMS} is the root mean square tetrahedron edge length (Flynn 1964, Siegel 1966a). Thus, for the case of annealing to tetrahedron sinks the defect annealing rate equation may be written as

$$\frac{d\bar{c}}{dt} = - 2\pi \bar{\epsilon} L_{RMS} N_s \bar{c} D_{OV} \exp (-E_V^m/kT). \quad (1)$$

It is clear from eqn. (1) that the sink efficiency may have an important effect upon the vacancy annealing kinetics. If, for example, $\bar{\epsilon}$ contains a Boltzmann factor it will exert a direct influence upon the measured effective migration energy for the annealing process. Therefore, the sink efficiency, and in particular its temperature dependence, needs careful consi-

deration in any quantitative analysis of defect annealing kinetics. In addition, since the climb mechanism by which vacancies are annihilated at stacking fault tetrahedra is most likely closely related to the climb of extended dislocations in low stacking fault energy, f.c.c. materials, a quantitative understanding of the climb efficiency of this process is of further interest.

In the present investigation, the average efficiency of stacking fault tetrahedra as vacancy sinks over the major portion of their growth has been measured as a function of temperature in the range $20^{\circ}\text{C} \leq T \leq 100^{\circ}\text{C}$ by using a direct electron metallographic technique (Siegel et al. 1968). The degree of tetrahedron growth in the vicinity of a free surface was measured using transmission electron microscopy and this was compared with the analytical solution to the diffusion equation describing the competitive annealing of the vacancy defects to the free surface and the growing tetrahedra. In this manner a unique value of $\bar{\epsilon}$ at each annealing temperature was obtained for the tetrahedra.

2. EXPERIMENTAL PROCEDURE

In order to measure directly the vacancy sink efficiency of stacking fault tetrahedra, a system was formed in which competitive vacancy annihilation at two different types of sinks (tetrahedra and a free surface) took place such that the effect of this competition on the resulting microstructure was independent of the diffusion coefficient of the migrating defects. The method used in the present investigation was described in detail in a previous article (Siegel et al. 1968) and, as such, will only be briefly outlined here.

An annealing system was created in which, as an initial condition, a uniform distribution of partially grown tetrahedra embedded in a uniform average concentration of supersaturated vacancy defects existed in the vicinity of, and adjacent to, a clean free surface. Subsequently, the remaining supersaturated vacancy defects were allowed to anneal competitively at both the surface and the tetrahedron sinks. In this manner, at completion of the vacancy annealing process there was a variation of final tetrahedron size with distance from the surface; the depth of this perturbation being determined by the vacancy sink efficiency of the stacking fault tetrahedra relative to that of the surface. (These initial and final states are represented schematically in fig. 1 of Siegel et al. (1969)). In order to obtain a quantitative measurement of the sink efficiency the appropriate diffusion equation for this system was solved analytically.

The problem was formulated by considering a semi-infinite slab containing a uniform density of stacking fault tetrahedra, N_s , of initial edge length, $L_0 = L(x,0)$, and a uniform concentration of mobile vacancy defects, $c_0 = \bar{c}(x,0)$, with diffusion coefficient, D . Since vacancy annihilation could take place at both the surface, at $x = 0$, and the tetrahedra, the diffusion equation could be written as

$$\frac{\partial \bar{c}(x,t)}{\partial t} = D \left[\frac{\partial^2 \bar{c}(x,t)}{\partial x^2} - 2\pi N_s \bar{\Gamma} \bar{\epsilon} L(x,t) \bar{c}(x,t) \right], \quad (2)$$

where the total vacancy loss consists of the divergence of the diffusion current in the volume and the loss due to the sink action of the tetrahedra. The additional factor, $\bar{\Gamma}$, in this second term represents the actual deviation from the assumption, made in obtaining eqn. (1), that the sink size is very small compared with the volume from which the vacancy defects

are being annihilated. Thus, $\bar{\Gamma}$ takes into account the growth of a tetrahedron relative to its sphere of influence and increases monotonically as a function of $(LN_s^{1/3})$ from its value of unity for $L = 0$. In eqn. (2) the term $\bar{\epsilon}$ represents the average sink efficiency of the stacking fault tetrahedra, and the sink efficiency of the surface was assumed to be unity. The validity of this assumption was experimentally verified by the observation that essentially no tetrahedron growth occurred at the specimen surface (see section 3).

An analytical steady state solution of eqn. (2) was obtained (Siegel et al. 1968, Siegel et al. 1969) by taking $\bar{\epsilon}$, D and $\bar{\Gamma}$ to be averaged constant quantities and using the boundary conditions; $L(0,t) = L_0$ (i.e., the initial tetrahedron size) for all t , and $\partial L(x,t)/\partial x=0$ at $x = \infty$. The solution obtained, written in terms of the fractional tetrahedron size, $w = L(x,t)/L_b$, where L_b is the final tetrahedron size in the unperturbed specimen bulk, is given by

$$x = \left[2\pi N_s \bar{\Gamma} \bar{\epsilon} L_b \right]^{-1/2} \ln \left(\frac{\sqrt{3} + \sqrt{w+2}}{\sqrt{3} - \sqrt{w+2}} \cdot \frac{\sqrt{3} - \sqrt{w_0 + 2}}{\sqrt{3} + \sqrt{w_0 + 2}} \right), \quad (3)$$

where $w_0 = w(x,0) = L_0/L_b$. Therefore, an analytical solution to the diffusion problem at hand was obtained in which all of the parameters besides $\bar{\epsilon}$ could be directly measured, providing a completely self-contained method for the determination of $\bar{\epsilon}$ for stacking fault tetrahedra.

Ribbon-shaped polycrystalline foils of COMINCO Grade 59 gold of 99.999 wt. % nominal purity were used for the investigation. The foils were shaped into standardized specimens (Siegel et al. 1968) for quenching with gauge sections approximately 8 cm long, 0.48 cm wide and 0.011 cm thick. After a cleaning in 50% nitric acid with a subsequent distilled water rinse, the specimen, mounted on a heavy copper frame inside of a

draught free box, was resistance heated for 1 hr at 930°C . With the specimen thus heated, the temperature uniformity along the gauge length was maintained uniform to $\pm 2^{\circ}\text{C}$. After the pre-quench anneal, the specimen was cooled to the quenching temperature, $(920 \pm 5)^{\circ}\text{C}$, and held for 2-3 min at approximately 0.5 cm above the surface of distilled water. The quench was accomplished by then dropping the entire mounted specimen in an edge-on direction into the water at $(24 \pm 1)^{\circ}\text{C}$ and immediately thereafter turning off the power to the specimen, which then remained at room temperature for (3.0 ± 0.5) min while necessary handling operations were performed. Subsequently, the specimen was aged for 15 min at $(60 \pm 1)^{\circ}\text{C}$ in order to completely nucleate and initiate the growth of the stacking fault tetrahedra throughout the foil.

The central part of the gauge length was then carefully cut into six rectangular samples (0.48 cm by 0.85 cm) to be used for obtaining the tetrahedron size vs. depth data. Since vacancies near the original specimen surface were lost due to the sink action of the surface during the quench, these samples were then electropolished for 5 min at 63°C in the standard cyanide electrolyte (Thomas 1962) to remove these perturbed surface regions. A thickness of $(16 \pm 1)\mu$, determined by a thickness vs. weight loss calibration, was removed from each surface in this manner and the requisite initial condition in these samples was thus obtained.

The initial tetrahedron size, L_0 , was determined from one of the remaining ends of the gauge length which had been given only the 15 min aging treatment at 60°C and subsequently stored at -15°C for 2 to 4 hours. These samples were then thinned in the cyanide electrolyte at

0°C over a period of about 30 min and immediately examined in the electron microscope so that essentially no further vacancy annealing (i.e., tetrahedron growth) took place prior to their observation. The final bulk tetrahedron size, L_b , was obtained from the other end of the gauge length after complete annealing (24 hr) at 60°C .

Specimens prepared in the above manner were used for each of the isothermal determinations of $\bar{\epsilon}$ at 20°C and 100°C . For the measurement at 20°C the six samples from the gauge length were annealed for 200 hr in a controlled temperature bath at 20°C . This bath consisted of a precision viscosity bath filled with silicone oil in which six identical copper cylinders containing distilled water were uniformly placed. The samples were placed in these cylinders during annealing as a precaution against any possibility of sample deformation resulting from the rapidly stirred oil over the rather long annealing times. The temperature of the water in the cylinders was maintained uniform to $\pm 0.1^{\circ}\text{C}$.

For the measurement of $\bar{\epsilon}$ at 100°C , and for two additional runs at 150°C and 200°C , an insulated annealing bath was constructed containing a low viscosity silicone oil (Dow Corning 550 Fluid) which was held constant to $\pm 0.1^{\circ}\text{C}$ at the temperatures used. The six matched samples, mounted on a holder, could be rapidly lowered into this stirred oil bath. Since the total vacancy annealing times at the higher temperatures were quite short, the isothermal measurement of $\bar{\epsilon}$ necessitated sample temperature rise times (i.e., the times taken by the samples to come up to the bath temperatures) which were relatively small. From previous work (Siegel 1966a) it was estimated that the annealing half-time at

40°C in the present samples would have been approximately 2 hr. Using an effective vacancy defect migration energy of 0.62 eV in the appropriate concentration range (Ytterhus and Balluffi 1965), the approximate times for the annealing of 50% of the quenched-in vacancy defects at 100°C, 150°C and 200°C were then calculated to be 170 sec, 18 sec and 3 sec, respectively. The sample rise-time was experimentally determined several times before and after each run using a dummy sample, identical to the actual ones, with a thermocouple spot-welded to it. This sample was rapidly lowered into the annealing bath in the same manner as in the run itself and the thermocouple output was recorded from a storage oscilloscope. The measured rise-times were (0.8 ± 0.2) sec, (0.65 ± 0.10) sec and (0.35 ± 0.05) sec for the 100°C, 150°C and 200°C annealing runs respectively (Jain 1969). It was estimated from available annealing data (Siegel 1966a) that the maximum amount of annealing which could have taken place during these rise-times was about 0.5%, 3% and 10%, respectively. Thus, to a good approximation these higher temperature anneals were isothermal.

In order to determine the tetrahedron size variation with distance from the free surface, caused by the competition for vacancy annihilation between the tetrahedra and the surface, an electrolytic sectioning technique was used. This technique has been described in detail elsewhere (Siegel et al. 1968). Known thicknesses could be removed from the samples by using a thickness removed versus weight loss calibration performed on a dummy sample identical to those used in the investigation. The relationship between the sample thickness and weight loss in the range of interest was found to be linear with a slope of (0.101 ± 0.005) cm/g. Thus,

thickness reductions, and hence sectioning capability near the free surface, of a few hundred Å were easily obtained in practice.

The tetrahedron sizes and densities and the electron microscope sample foil thicknesses were obtained directly from the electron micrographs using standard procedures.

3. RESULTS

The results of the annealing runs at $T_A=20^\circ\text{C}$ and $T_A=100^\circ\text{C}$ are shown in fig. 1 and fig. 2, respectively, in which the measured root mean square tetrahedron edge length, L_{RMS} , is plotted versus the distance, x , from the competitive surface sink. The initial and final bulk tetrahedron sizes shown at $x=0$ and $x=\infty$, respectively, were determined from the measurement of from 4000 to 5000 individual tetrahedra for each datum point. The data points in the range $0 < x < \infty$ were each determined from the measurement of 1000-1500 tetrahedra, with each of these points having approximately the same statistical weight in terms of specimen volume examined. Error bars corresponding to the mean deviation of the data are presented in all cases.

The measured tetrahedron density, N_S , in each of the runs was found to be constant after the initial post-quench aging treatment at 60°C for 15 min and thus, the observed effects resulted only from the growth of the tetrahedra in the vicinity of the free surface, with no further nucleation having taken place. The mean deviations in the measured tetrahedron densities, shown in fig. 1 and fig. 2, represent random variations from region to region within the specimen. The observed uniformity of tetrahedron density in each specimen, moreover, verified that the removal of 16μ from the original specimen surface after quenching was

sufficient to completely remove the perturbed specimen volume resulting from the sink action of the surface during quenching. The quenched-in vacancy concentrations were calculated from the tetrahedron density and final bulk tetrahedron edge length for the 20°C and 100°C runs and values of $(2.7 \pm 0.5) \times 10^{-4}$ and $(2.8 \pm 0.6) \times 10^{-4}$ were obtained, respectively. These values agree well with that to be expected for a rapid quench from 920°C (Balluffi *et al.* 1970).

The theoretical curves in fig. 1 and fig. 2 were calculated from eqn. (3) for the various values of $\bar{\epsilon}$ shown to compare with the directly measured variation of the tetrahedron size with distance from the surface sink. For the $T_A = 20^\circ\text{C}$ run the measured values $L_o = 289\text{\AA}$, $L_b = 440\text{\AA}$, $N_s = 1.36 \times 10^{15} \text{cm}^{-3}$ and $\bar{\Gamma} = 2.12$ were used, and for the $T_A = 100^\circ\text{C}$ run, $L_o = 247\text{\AA}$, $L_b = 442\text{\AA}$, $N_s = 1.41 \times 10^{15} \text{cm}^{-3}$ and $\bar{\Gamma} = 2.08$ were used for this calculation. The values of $\bar{\Gamma}$ were taken in each case as the arithmetic mean of the initial and final values of this parameter determined directly from the experimental values of L_o , L_b and N_s .

By a comparison of the experimental data points of fig. 1 and fig. 2 with the theoretical curves calculated for various values of the tetrahedron sink efficiency, $\bar{\epsilon}$, which was the only undetermined parameter, values of $\bar{\epsilon}$ at each of the annealing temperatures, T_A , were determined. It was concluded that $\bar{\epsilon} = 0.5 \pm 0.1$ at $T_A = 20^\circ\text{C}$ and $\bar{\epsilon} = 0.9 \pm 0.1$ at $T_A = 100^\circ\text{C}$, where these sink efficiencies are the averages of this parameter over a range of vacancy concentration corresponding to the observed portion of tetrahedron growth which took place during each run. The initial vacancy concentration for the $\bar{\epsilon}$ determination was 1.5×10^{-4} in the 20°C run and 1.9×10^{-4} in the 100°C run.

The assumption, made in writing eqn. (2), that the surface (in this case predominantly orientations close to (100) due to the strongly preferred orientation of the rolled foil specimens used) acted as a perfect vacancy sink can be seen to be reasonably justified from the data of fig. 1 and fig. 2. It can be seen from these data, especially those of fig. 1, that little or no tetrahedron growth appears to have occurred at the specimen surface during the experiment. Thus, the analytical model used to evaluate $\bar{\epsilon}$ seems to be consistent with the experimental data.

Additional annealing runs which were performed in an attempt to measure $\bar{\epsilon}$ at 150°C and 200°C were unsuccessful. The surface specimens for these runs were found to contain no tetrahedra. This observed tetrahedron loss cast some doubt about the stability of the tetrahedra near the free surface at these annealing temperatures. In order to check their stability, thin foils containing partially grown tetrahedra were heated in air at 350°C for 2 hr and at 210°C for 12 hr. A careful re-examination, however, of these foils revealed that the tetrahedra were essentially stable at these temperatures and no significant change in their density was observed. In these two runs the samples had to be rapidly lowered into the constantly stirred hot oil bath in order to meet the stringent requirement of short rise-times. It is possible that this procedure was sufficiently drastic in the case of these runs to generate stresses large enough to collapse the tetrahedra in the sample volume near the surface with their subsequent loss. Therefore, it was not possible to measure $\bar{\epsilon}$ for the tetrahedra above 100°C using the present techniques.

In addition to this complete loss of tetrahedra near the surface in the 150°C and 200°C runs, a somewhat lower tetrahedron density than that found in the bulk was observed near to the free surface in the 100°C run. This tetrahedron loss may have caused the two experimental data points in fig. 2 at $x = 290\text{\AA}$ and $x = 420\text{\AA}$ to lie above the theoretical curve for $\bar{\epsilon} = 0.9$, while the rest of the data points conform reasonably to its shape. However, the sink efficiency measurement at 100°C does not seem to have been significantly affected by this effect and the measured value of $\bar{\epsilon} = 0.9 \pm 0.1$ appears reliable.

4. DISCUSSION

The temperature dependence of the vacancy sink efficiency of stacking fault tetrahedra in quenched gold may be seen by comparing the values for $\bar{\epsilon}$ measured at 20°C and 100°C in the present investigation with the two measurements of $\bar{\epsilon}$ at 60°C reported previously (Siegel et al. 1968, Siegel et al. 1969), as shown in the $\ln \bar{\epsilon}$ versus $1/kT$ plot of fig. 3. It can be seen that the sink efficiency behaves phenomenologically over the temperature range of the measurements as $\bar{\epsilon} = A \exp(-\Delta E/kT)$, where $A = 8.0$ and $\Delta E = 0.07$ eV. The values of $\bar{\epsilon}$ compared in fig. 3 were measured over similar vacancy concentration ranges with a mean initial concentration of $c_v = (1.6 \pm 0.4) \times 10^{-4}$.

Although measurements of $\bar{\epsilon}$ above 100°C were unsuccessful, some insight into the behavior of $\bar{\epsilon}$ at higher temperatures may be obtained from the observations of Meshii (1965) and Yoshinaka et al. (1967) that the final attained size of tetrahedra in the bulk crystal decreased for aging temperatures above ~ 200 -250°C for essentially constant quenched-in vacancy concentration and tetrahedron density. A similar observation

was made in the present investigation for aging at 200°C . Since the apparent ability of the tetrahedra to grow decreases at these temperatures, presumably by unfavorable competition with other vacancy sinks, it may be concluded that the sink efficiency decreases again for temperatures above $\sim 200^{\circ}\text{C}$.

The most reasonable model for the growth of stacking fault tetrahedra is that of the nucleation and subsequent vacancy supersaturation induced migration of $1/3$ vacancy jog lines, or V-ledges, across the faces of the tetrahedron (de Jong and Koehler 1963a, Kuhlmann-Wilsdorf 1965). In general, both ledge nucleation and migration may be activated processes and may depend upon the vacancy supersaturation at the tetrahedron. While the results of the present investigation are consistent with this model, it cannot be concluded whether the measured effective activation energy, ΔE , of the climb process leading to tetrahedron growth in the temperature range $20^{\circ}\text{C} \leq T_A \leq 100^{\circ}\text{C}$ is associated with ledge nucleation, migration or a combination of these. It is, however, interesting to note that the value of $\Delta E = 0.07 \text{ eV}$ is comparable in magnitude to estimates (Kuhlmann-Wilsdorf 1965) of the line energy per atomic length of a V-ledge in gold, $0.05 \text{ eV} \lesssim E_{\rho} \lesssim 0.14 \text{ eV}$.

The presence of an exponentially temperature dependent tetrahedron sink efficiency brings to light a problem with respect to the measurement of vacancy defect migration energies from annealing studies in quenched gold, or, for that matter, other low stacking fault energy, f.c.c. metals. As pointed out in sec. 1, the defect annealing rate to tetrahedron sinks is proportional to the product of the sink efficiency, $\bar{\epsilon}$, and the vacancy defect diffusion coefficient, D_V . Such a functional

relationship would, of course, also exist for the annealing of super-saturated vacancies to other types of sinks (e.g., extended dislocations), where the vacancy sink or climb efficiency of the particular sink in question should be substituted. Under such conditions the measured effective activation energy, $E_{\text{eff}}^{\text{m}}$, for the annealing process will contain, in addition to the defect migration energy, the activation energy associated with the vacancy defect annihilation process at the active sinks. It can be concluded from the present results that this is likely to have been the case with previous measurements of $E_{\text{eff}}^{\text{m}}$ in gold, in the annealing temperature range $20^{\circ}\text{C} \leq T_{\text{A}} \leq 100^{\circ}\text{C}$, under conditions where vacancy defect annealing took place at stacking fault tetrahedra (see for example Ytterhus and Balluffi (1965) and Kauffman and Meshii (1965)). In addition, the possibility exists that vacancy annealing to extended dislocations (Wang et al. 1968) and dislocation loops (Siegel 1966) may also give rise to an effective activation energy for the annealing process which contains a similar contribution from the climb efficiency of the sink. Since the activation energy for the climb process at tetrahedra measured in the present investigation, 0.07 eV, is not very much larger than the error limits, ± 0.03 eV, which have been quoted for such $E_{\text{eff}}^{\text{m}}$ measurements, it is difficult to draw detailed conclusions at this time regarding this problem. However, it is likely that the activation energy associated with the vacancy defect migration which predominates at high concentrations ($c_{\text{v}} \approx 5 \times 10^{-5}$) in quenched gold is smaller (by ~ 0.07 eV) than the values of $E_{\text{eff}}^{\text{m}}$ (~ 0.62 eV) measured by various investigators (de Jong and Koehler 1963b, Kauffman and Meshii 1965, Ytterhus and Balluffi 1965) for the annealing to tetrahedra of

vacancies in this concentration range. Additional experiments, which either take into account the properties of the active sinks or are truly independent of them, are clearly needed before such problems may be unambiguously resolved.

Specific information regarding the efficiency of dislocation climb is limited. It is apparent from the available data that climb is an efficient process in both high and low stacking fault energy, f.c.c. metals, but tends to be somewhat more difficult in the latter case (Balluffi 1969). This is not surprising in light of the probable greater difficulty in nucleating and/or propagating jogs on the extended dislocations in the low stacking fault energy metals. In line with this, Washburn and Yokota (1969) have recently observed that the annealing of stacking fault loops in gold is not diffusion limited, as is the case in aluminum (a high stacking fault energy metal), but is consistent with a model in which the rate controlling step for climb is jog nucleation with an energy of ~ 0.13 eV. The direct measurements of the sink efficiency of stacking fault tetrahedra have shown that while tetrahedra are relatively efficient vacancy sinks in the presence of large vacancy supersaturations, their sink or climb efficiency is generally less than unity and the climb process is thermally activated with an effective activation energy of 0.07 eV. These results are consistent with the previous work on the efficiency of dislocation climb in gold.

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FIGURE CAPTIONS

- Fig. 1. The root mean square tetrahedron edge length, L_{RMS} , as a function of distance, x , from the competitive surface sink after annealing at $T_A = 20^\circ\text{C}$. The experimental data are compared with the solution, eqn. (3), of the theoretical diffusion problem for various values of the tetrahedron sink efficiency, $\bar{\epsilon}$.
- Fig. 2. The root mean square tetrahedron edge length, L_{RMS} , as a function of distance, x , from the competitive surface sink after annealing at $T_A = 100^\circ\text{C}$. The experimental data are compared with the solution, eqn. (3), of the theoretical diffusion problem for various values of the tetrahedron sink efficiency, $\bar{\epsilon}$.
- Fig. 3. A plot of $\ln \bar{\epsilon}$ versus $1/kT$ showing the observed temperature dependence of the tetrahedron sink efficiency, $\bar{\epsilon}$. In the temperature range $20^\circ \leq T_A \leq 100^\circ\text{C}$, the data fit the relation $\bar{\epsilon} = A \exp(-\Delta E/kT)$, where $A = 8.0$ and $\Delta E = 0.07$ eV.

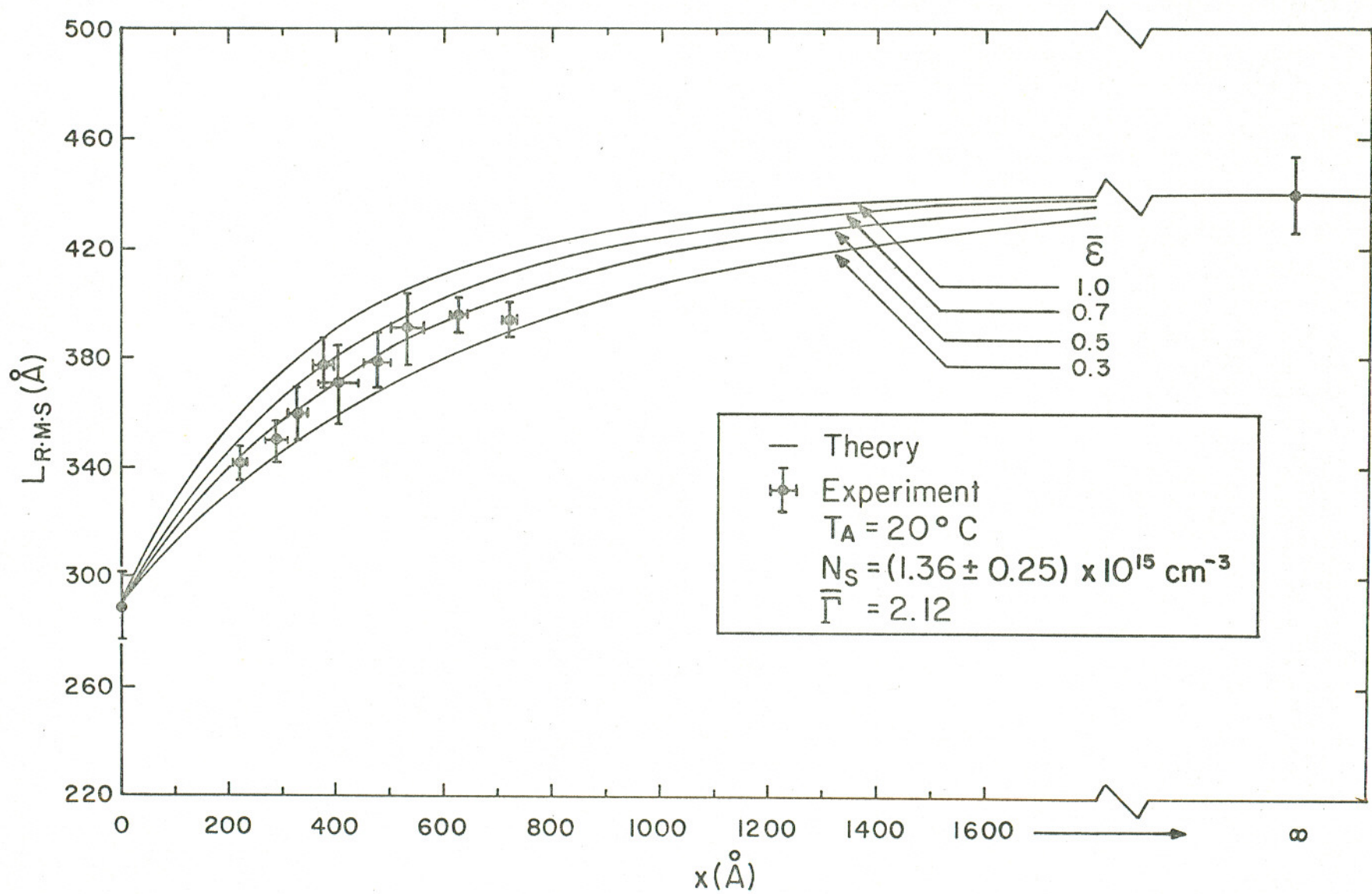


Figure 1

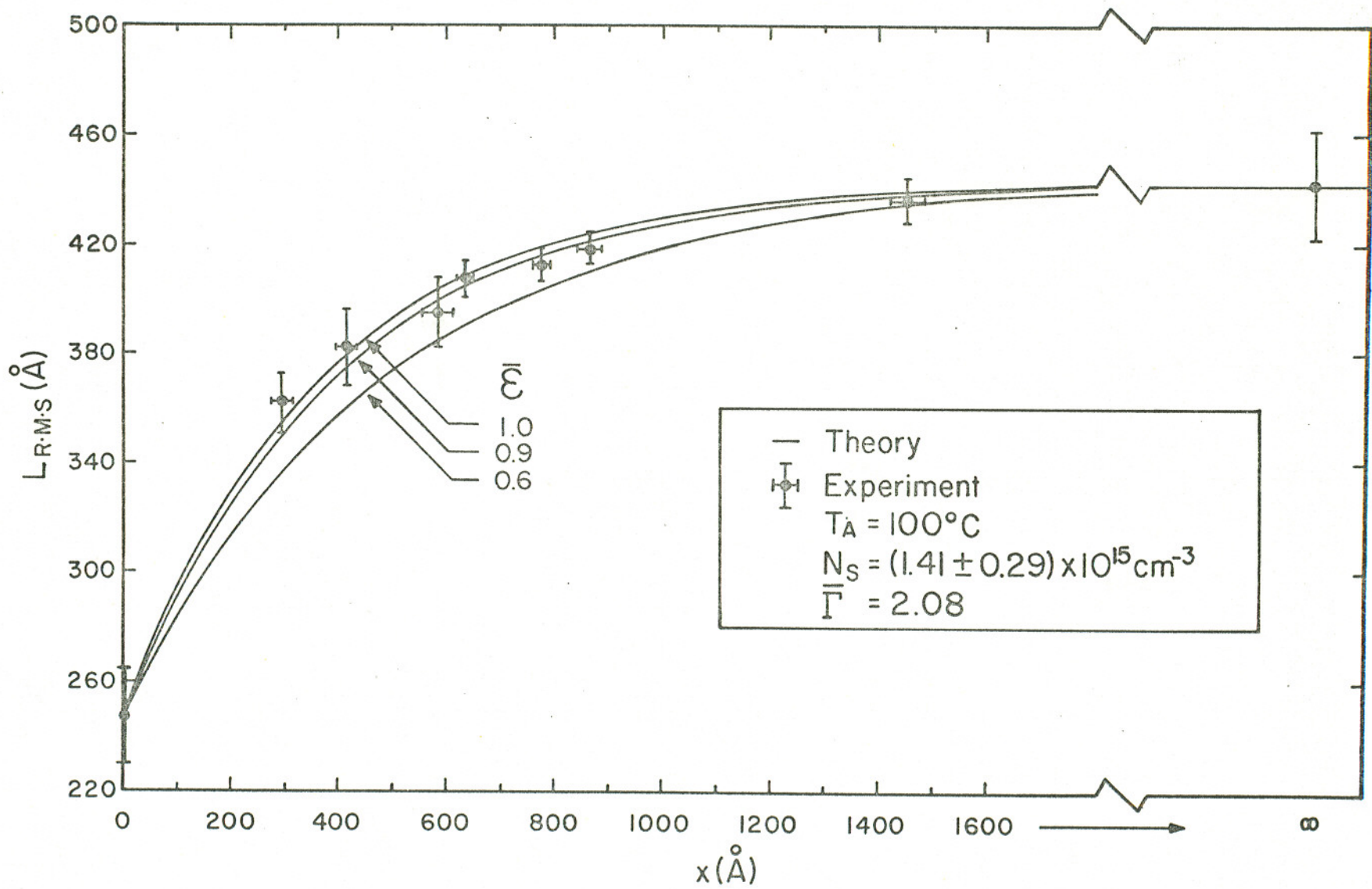


Figure 2

Figure 3

