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to the

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for

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The Fundamentals of Radiation Damage

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Professor A. Sosin

Department of Physics

and

Division of Materials Science and Engineering

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The second year of operation under the support of the U. S. Atomic Energy Commission has been marked by a gratifying and exciting movement from equipment development to full data acquisition: with the appropriate meaning applied to these terms, this refers to our efforts in theory as well as experiment. The progress in several different categories are presented below.

EXPERIMENTAL EQUIPMENT. During this last year, liquid helium cryostat I (brought with the principal investigator from North American Rockwell Science Center and modified at Utah) has been brought into full operation and used for the dissertation studies of Mr. D. Parkin. Liquid helium cryostat II, developed entirely at Utah, is completed but is momentarily plagued with a small vacuum leak. (The characteristics of cryostat II were described in the report of November 19, 1969--COO-1800-06). Liquid helium cryostat III is about half finished. Room temperature cryostat IV (obviously not a cryostat at all, but called this for convenience) is complete and currently being used in studies of Young's modulus and internal friction. Liquid nitrogen cryostat V is about half complete. Cryostat III should be finished in the next month or so; cryostat V should be finished before the end of summer, possibly before the beginning of summer. Thus we are nearly in a completely operative position with regard to irradiation holders.

Temperature control is always important in irradiation experiments. Again, we are in superb condition here. Cryostat I and II apparently control temperature to better than 0.01°K ; a full appreciation of the extent of the control is difficult to achieve. Cryostat III controls temperature, apparently, to about 0.001 degree; again this control figure is arrived at indirectly. In any case, both the construction details pursuant to temperature control and the electronics involved appear to be excellent. No further equipment

for temperature control should be necessary for cryostats IV and V.

The data acquisition system for resistivity measurements has been discussed in previous reports. It is functioning excellently.

Probably the most impressive equipment development during the last year has been in the measurement of Young's modulus and internal friction. The system consists of a regenerative, constant amplitude drive system for flexural vibration of a foil sample, using electrostatic drive and frequency modulated pick-up. Strain amplitudes of $\sim 10^{-6}$ are presently in use. For future intended studies of amplitude-dependence, the system can provide strain amplitudes of at least 10^{-4} and probably of 10^{-3} . The modulus is monitored directly on a digital frequency counter, averaging over 1000 cycles and displaying the natural period; further accuracy can be obtained by averaging over 10^4 cycles if other experimental factors allow (i.e., if the modulus is not changing too rapidly). The sample is generally vibrated in a self-driven, feed-back mode for period measurements; the square of the drive voltage required to maintain constant amplitude is monitored on a digital volt meter and is proportional to the internal friction. As a further check, the feed back system can be interrupted and the sample vibration decay monitored on a memory scope to give the internal friction absolutely, but less accurately than in the self-driven mode.

A block diagram of this apparatus is given in Figure 1. Much of the equipment has been assembled in our laboratory.

In the use of computer techniques, the development of computer-based, diffusion-limited programs is generally fully completed although continual advancement will be sought. Closely allied with this, computer techniques for data smoothing and display have been developed. Both of these developments utilize the Univac 1108 computer facilities of the University of Utah.

Further computer techniques using the Hewlett-Packard desk computer in the Department of Physics for data reduction are in use as well.

ACCELERATOR FACILITIES. During the last year, the Van de Graaff accelerator and its facilities have been improved significantly. Beam deflection and focussing systems have been developed which permit very steady and constant operation. Steady conditions are vital to the experiments on dislocation pinning, particularly at elevated temperatures. A plot of electron fluence vs time is appended in Figure 2 to show the steadiness of operation presently routinely available. These data are taken at minimal current conditions-- conditions least conducive to steady operation.

The operation of the Van de Graaff accelerator below 0.5 MeV requires further improvement. To date, we have had no call for operation below this energy and have been unwilling to invest the needed time to improve the accelerator for lower energies. During the forthcoming year we plan to insert a variable electrical shorting arrangement which should result in improved operation at low energy.

The housing for the LINAC has been completed. This spacious laboratory adjoins the Van de Graaff facility and shares a common control room. We are presently assembling the LINAC. Most of the attendant equipment is available. The most notable exception is a four-inch quadrupole magnet still to be purchased.

The work on both accelerators and the housing have been provided by the University.

RESEARCH PROGRESS AND REPORTS.

The dissertation work on the recovery of the electrical resistivity of electron irradiated copper in Stage I has been completed by Mr. D. Parkin. A summary of the experiments which were performed appears in Table I, including the electron energies used and the initial defect concentrations injected. The amount of data obtained in these experiments is very large and data reduction is still in progress. The features which emerge in advance of full analysis are

- 1.) The amount of recovery effected in the substages of Stage I is energy dependent; this effect has, of course, been established previously by other investigators.
- 2.) The early portions of I_d is relatively energy independent.
- 3.) The main effects of energy are found in the transition region between I_d and I_e . Here the recovery at lower energy occurs more rapidly than at higher energy.
- 4.) Substage I_e is little effected by electron energy.
- 5.) The total amount of recovery in Stage I is relatively insensitive to energy
- 6.) The main effect of initial defect concentration occurs in I_e , also previously established by others.
- 7.) Overlap of isothermals taken at different energies can be made to overlap with a time-temperature compensation, using an activation energy of 0.117 eV, as suggested by Corbett et al. A typical isothermal recovery curve taken in the present study and a composite recovery curve, the latter extending over more than seven orders of magnitude in time, are included in this report.

All of the data taken in these experiments have been plotted by the

Univac 1108 digital computer. This includes seven preliminary recovery vs equivalent time plots, such as the one appended here. Since we are pressing toward high resolution in the data acquisition system, smoothing procedures which eliminate random fluctuations are in order and are being applied. In this smoothing procedure, least square fits are made to the data, the fits using various sets of functions and not merely confined to the dominant exponential time decay which would suffice for first order processes.

Some typical data obtained in the experiments of D. Parkin are given in Figs. 3-6. In Figure 3, the resistivity of an unirradiated sample is displayed as a function of time at the annealing temperature of 28.8°K . By way of comparison, Figure 4 shows the annealing at 30.2°K of a sample irradiated at 0.6 MeV to an initial fractional concentration of 7×10^{-6} .

In Figure 5, we show the result of a series of annealing experiments performed on a sample, the sample having been originally irradiated to an initial fractional concentration of 7×10^{-6} at 1.0 MeV. The data are displayed as the percentage of initial damage on the ordinate vs. the "equivalent time", extending over several decades of time. For comparison, Figure 6 shows the analogous results for irradiation at 0.6 MeV. A comparison of Figure 5 and 6 brings out many of the features listed above. The data in Figures 5 and 6 are raw data.

Following completion of the display and smoothing of the experimental data, these data will be used in the diffusion-based annealing kinetics program which has been developed in the dissertation activities of Mr. Thompson. A key to the importance of this framework lies in the agreement in this analysis using a large quantity of precise data relevant to low initial defect concentrations to the very high dose data of H. Wollenberger et al. of the University of Aachen. The various reaction radii for

recombination and clustering have overlapping degrees of importance in the two cases and simultaneous agreement should remove much of the apparent arbitrariness inherent in a theory having several parameters. These analysis should be completed by the end of summer .

Concomitant with the above kinetic analysis, Mr. Thompson has pursued random walk calculations using Monte Carlo techniques. Some details of this calculation have been given in COO-1800-06. This work is also nearing completion.

In COO-1800-06, the work of Mr. P. Cannon on the bombardment of highly dilute alloys was cited. The system for fabricating and evaluating these alloys is largely assembled and production of alloys is about to start. In the procedure, we are stressing the importance for control: a particular alloy will be developed along side an unalloyed sample to assure, as far as feasible, that the difference may be ascribed to alloy content. This is particularly important when dealing with alloying contents of 10^{-4} , as planned.

In COO-1800-06, the work of Mr. R. Alldredge concerning Mattheisen's Rule was described in fair detail, as well. Mr. Alldredge has concentrated his attention recently to the preparation of samples for the experiments described in that report. Irradiations should be underway well before the beginning of summer.

During the past year, Dr. H. M. Simpson and the principal investigator have devoted considerable attention to the theoretical basis of much of annealing theory, encountered in irradiation studies and elsewhere. A detailed report of this study is included here: COO-1800-07. This article "Defect Mobility and Reaction: Diffusional and Rate Theory Formulations in One and Three Dimensions" is to be published shortly in Radiation Effects.

Using the methods described in this article, Simpson and Sosin have gone on to the analysis of the very recently reported observations of D. O. Thompson and O. Buck, North American Rockwell Science Center. Thompson and Buck bombarded high purity copper at various temperatures between 80°K and 400°K, using gamma rays. They observed a minimum in the pinning rate vs. temperature plot. This minimum cannot be explained by any single activated process and is difficult to explain in any case. We have been able to give a fully quantitative explanation of this observation in terms of thermal conversion of one form of interstitial to another. Furthermore, it is necessary that the two forms of interstitials migrate in three dimensions. The role of the crowdion--central to previous recovery models--is cast in serious doubt. The analysis has been incorporated in a second article to be published shortly in Radiation Effects entitled "Thermal Conversion of Interstitials"; COO-1800-08.

The minimum referred to should appear in resistivity measurements, but in the form of a maximum in a plot of damage rate at different temperatures vs. bombardment temperature. Mr. G. Youngblood is preparing the experiments intended to search for this maximum and will use Cryostat II in this work. The analysis, based on the parameters used by Simpson and Sosin, has been carried out for this study. The prediction of this analysis is for a maximum which is less dramatic than the minimum observed in internal friction (i.e., dislocation pinning) experiments but more direct in interpretation. There is no significant foreseeable problem in performing these experiments at an early date beyond the vacuum difficulty in Cryostat II.

Some of the most exciting developments in this program have been in the area of experiments involving observations in the changes of Young's modulus and internal friction under bombardment. These experiments are being

carried out by Dr. Simpson with the collaboration of Lt. G. Edwards and Mr. S. Seiffert. Early preliminary results were cited in COO-1800-06. Since then, a set of irradiations have been performed at 17, 37, 57, 77, 101, and 125°C and using 1 and 2 MeV electrons. Both internal friction and Young's modulus are monitored every three seconds during bombardment (or afterwards). The experiments were performed within a one week period, demonstrating the fact that whole areas of study may now be investigated quickly and in-depth with the present apparatus. It is entirely possible that data analysis will be the limitation in this work! The data derived from these experiments are presently being analyzed. Pending completion of this analysis, it appears that several features are influencing the results: interstitial diffusion in the lattice to dislocations, interstitial diffusion along dislocation lines (somewhat slower than in the lattice), vacancy diffusion to dislocations, etc. These experiments have been performed on "commercial high purity" copper, obviously much less pure than the material Thompson and co-workers used in gamma irradiation experiments: yet the results seem to be reasonably similar when account is made for the significantly different dose rate.

Some early data obtained in this work is given in Figs. 7 and 8. Figure 7 shows the decrease of the natural period of oscillation (i.e., the increase of Young's modulus) in nanoseconds, on the ordinate, vs. the time of irradiation at 37°C upon irradiation with 1.0 MeV electrons. The display is through the data points alone--no connecting lines have been drawn--thereby emphasizing the extensiveness of the data. Periodic "blips" mark the hand adjustment of phase control and are to be considered spurious. Figure 8 shows the parallel behavior of the drive voltage, on the same sample, needed to maintain constant amplitude of oscillation. The close similarity of

the period in Figure 7 and the decrement (square of the drive voltage) is consistent with the vibrating string model for dislocation pinning.

Our small scale work on void formation in metals has progressed to the point that the irradiation housing--"Cryostat VI"--is operative and preliminary hydrogen injections have been made, using a 200 KeV Cockcroft-Walton accelerator. The initial material being studied is aluminum. The work has continued at a low level since the funding for this work has been drawn from internal sources. We would like to devote more effort to this project--equivalent to one graduate student beyond that specified in the budget--since the techniques are evidently satisfactory. Our emphasis would be on the effects of selected impurity additions in "well-characterized" metals on void formation. The techniques include transmission electron microscopy and small angle x-ray scattering. In addition, we are considering the possibility of using scanning electron microscopy to investigate the effects of strain on void formation and migration.

Table I

Series	Electron Energy in MeV	Dose $\Delta\rho$ Damage $\times 10^{-10} \Omega\text{cm}$	Fluence $\times 10^{-17} \text{e/cm}^2$	% Left After 53° K	% Left After 70° K
A	1	6.6	1.2	14.58	12.36
	1	21.2	4.0	13.73	13.43
AA	1	6.7	1.2	14.38	13.30
	1	21.1	4.0	13.71	13.20
B	0.6	7.0	4.4	13.97*	--
	0.6	21.2	16	12.59	12.94
BB	0.6	6.8	4.4	15.56*	--
	0.6	21.2	15	12.75	12.67
C	0.6	76.8	63	12.70	12.35
D	1.4	21.4	3.3	12.80	12.40

*This data is in question

INTERNAL FRICTION - Flow Chart

FLUENCE VS TIME
1. MeV
RUN #11

MICROVOLTS