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MASTER

A NEW MECHANISM FOR INTERNAL FRICTION*

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Abstract

Simultaneous measurements of damping and elastic modulus of copper as effected by electron irradiation above room temperature have been made. These data do not follow the standard analysis, using the Granato-Lucke theory for damping, in which point defects, created by irradiation, are presumed to act as firm pinning points on dislocation lines. It is proposed instead that these defects are dragged along by the dislocation line moving under oscillating stress.

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The analyses of a large number of experiments on internal friction in metals have been based, with remarkable success, on a theoretical formulation of Koehler,[1] amplified in detail by Granato and Lucke,[2] the G-L theory. This theory, a string-model for dislocation bowing under applied stress, is best known for its predictions, at reasonably low frequencies, for the strain amplitude-independent decrement and modulus change, δ_I and $(\frac{\Delta E}{E})_I$, and for the higher strain amplitude, amplitude-dependent decrement and modulus change, δ_H and $(\frac{\Delta E}{E})_H$:

$$\delta_I \quad = \quad a\, B\, \omega \Lambda L^4 \tag{1}$$

$$(\frac{\Delta E}{E})_I \quad = \quad b \Lambda L^2 \tag{2}$$

and

$$\delta_H \simeq (\frac{\Delta E}{E})_H \simeq \frac{c\Lambda}{L\varepsilon_o} \exp(-\frac{d}{L\varepsilon_o}). \tag{3}$$

B is a viscous damping constant, ω is the angular drive frequency, Λ is the total length of dislocation line per unit volume, L is the average length of dislocation between pinning points, and a, b, c and d are constants (see Ref. 2). The L^4 and L^2 dependences in Eqs. (1) and (2) are watermarks of the G-L theory. Irradiation experiments are particularly well suited for testing this L^4-L^2 prediction since the accretion of defects on dislocation lines during bombardment or subsequent annealing provides a controlled method for apparently systematically shortening the loop length, L, while not affecting any other parameters. If we let

$$Y \equiv \frac{\Delta E/E}{(\Delta E/E)_o} \tag{4}$$

and

$$Z = \delta/\delta_o \ , \qquad (5)$$

the G-L theory predicts a proportionality at low strain amplitudes between Y^2 and Z during irradiation. (The subscript I has been suppressed; the subscript o designates initial values. Background contributions to the decrement or modulus are presumed to be subtracted.) On occasion, such fits have been reported;[3] more commonly, the proportionality has not been obeyed. By invoking the concepts of two dislocation types,[4,5] further agreement, particularly with Eqs. (1) and (2), has been achieved at the expense of introducing more parameters into the analysis.

A second concern with the G-L theory centers on its prediction of linear frequency dependence of δ_I. The reported values over a relatively wide range of frequencies have shown little, if any, dependence on frequency, at relatively low frequency (e.g., near or below 1 kHz).

The observations reported here show that the G-L theory must be amended or that a new damping mechanism must be considered.

In the experiments reported here, copper foils were irradiated in a configuration similar to that reported previously by Sosin and co-workers.[4] (However, the method of sample oscillation was electrostatic in the present experiments, rather than magnetic, so that no iron foil was needed.) Data points were taken every three seconds; only a few of the data points are displayed in Fig. 1. The samples were annealed to 725°C prior to the initial irradiation and to 460°C between irradiations, in place. Little or no amplitude dependence was found in the strain amplitude range employed here, as determined by varying the drive by a factor of six. Clearly Eq. (3) does not apply to the present work.

The main experimental results, which lead to the conclusion that the G-L theory does not extend to these data, are presented in Fig. 1, a plot of Y^{-1} versus both time and Z^{-1} for five irradiations at the indicated temperatures. According to Eqs. (1), (2), (4), and (5), one would expect Y^{-2} versus Z^{-1} to be linear. Fig. 1 demonstrates that such a relationship is not correct. The curves for the lower temperature irradiations are better described by a Y^{-1} proportionality to Z^{-1}, while a power Y^{-n} proportionality to Z^{-1}, with $n > 1$, is better at higher temperatures.

The data in the inset of Fig. 1 were obtained during the course of the irradiations. But the importance of this figure is that such a plot is free from considerations of defect diffusion models since both Z and Y should each reflect, simultaneously, the number of defects on dislocation lines independent of how these defects arrived there. In contrast, the main data in Fig. 1 show the actual time-dependence of Y^{-1}. Note the excellent proportionality between Y^{-1} and time, except at initial times, over the range of times shown. A plot of Z^{-1} versus time shows a similar linearity for early times but the simple irradiation temperature dependence of the main plot in Fig. 1 is less clear.

The data of Fig 1 were obtained using a tough pitch, electrolytic 99.9% grade copper sample; a second sample of 99.999% (AS and R) purity was used to obtain the results shown in Fig. 2. The linearity of Z^{-1} and Y^{-1} on time, after transients, is again apparent.

We note that impurities play a minor role in these data. This observation, arrived at on comparison of Figs. 1 and 2, confirms the conclusion of Thompson et al.[3] deduced indirectly after a detailed analysis of their data on gamma-irradiated copper at 11 kHz. We believe that the minor impurity effect observed here is due to different dislocation arrangements in the two samples.

The hypothesis that the proportionality of Y^{-1} or Z^{-1} on t may be due in some manner to a constant rate of defects accumulated on dislocations by atomic displacements directly in the region of dislocation is ruled out by Fig. 3. Here the sample was irradiated for 22 seconds. The beam was then shut off, but the change in Y^{-1} continued with no change in character initially. Clearly diffusion over long distances is involved. This is further implied by an Arrhenius plot of ln (dY^{-1}/dt) versus inverse temperature which yields a straight line with slope of about 0.17 eV; the implication of this low energy is discussed below.

It is highly reasonable to conclude, therefore, that dY^{-1}/dt and dZ^{-1}/dt are measures of the rate at which defects are added to dislocation lines. The relative rates at which defects are added at 1 and 2 MeV are then well predicted by standard radiation damage displacement cross sections.

The experimental results presented here are supplemented by a considerable amount of further observations which illustrate the complex roles of irradiation temperature, purity content, annealing temperature, etc. The theoretical model which explains these observations is correspondingly complex. Therefore, we do not propose to present a full model here to explain these dependences; rather we shall merely indicate some aspects of this model, which suffice to explain the observations reported in this letter, by treating a limiting case.

The major feature of our model is that damping of dislocations on which point defects -- interstitials and, probably, vacancies -- have accumulated, is determined mainly by the damping characteristics of the point defects being dragged with the oscillating dislocation line, rather than with the line friction itself. In this spirit, the limiting case of our model is treated by a force equation where the force is presumed to be concentrated entirely on the n dragging points (i.e., point defects), resulting in a viscous behavior given by

$$(B_o + nB_d)\,\frac{dy}{dt} = \sigma b L \tag{6}$$

where B_d is the damping constant for each of the n dragging points, B_o is the damping constant appropriate in the absence of point defects, and L is the length of dislocation between firm anchor points (e.g., dislocation nodes). In addition, σ is the applied stress of angular frequency, ω.

$$\sigma = \sigma_o \sin \omega t \tag{7}$$

$\vec{b}$ is the Burger's vector of the dislocation; y is the displacement of the dislocation from its position in the absence of applied stress, and t is time.

In the full theoretical treatment, y is obviously dependent on position along the dislocation line, through the inclusion of dislocation line tension and through the boundary conditions at the two ends of the dislocations; these omissions in our extreme case treatment do not effect the conclusions in any significant manner.

The strain associated with the dislocation motion in this treatment is

$$\epsilon_{dis} = \Lambda b \, \bar{y} \quad , \tag{8}$$

and the damping is

$$\delta = \frac{E}{\sigma_o^2} \oint \epsilon_{dis} \, d\sigma = \frac{\pi E \Lambda b^2 L}{\omega(B_o + nB_d)} \quad . \tag{9}$$

The important features of this model are 1) the frequency dependence, ω^{-1}, is inverse to the normal G-L theory, implying that the dragging point effects as formulated here becomes less important at higher frequency (the full treatment shows that the effect also becomes less important at still lower frequencies) and 2) Z^{-1} increases linearly with the number of dragging points, n. The last point explains the general linearity of Z^{-1} with time when cognizance is taken that a steady state is quickly established in these experiments in which the rates of creation of point defects, their arrival at dislocations, and their loss from dislocations are in constant ratio (this can also be demonstrated analytically). The activation energy of 0.17 eV obtained from the Arrhenius plot of ln $\frac{dY^{-1}}{dt}$ versus inverse temperature is, we propose, the difference between the diffusion of point defects to dislocations minus the energy of migration down dislocations.

Note that this limiting case model is inadequate to treat the behavior of the modulus defect since the line tension of the dislocation was ignored in Eq. (6). More complete analysis indicates that Y^{-1} is proportional to time at relatively early times, then becomes even more strongly dependent on time subsequently, with a limiting time dependence of $Y^{-1} \propto t^{\frac{3}{2}}$. Thus Y^{-1} is a stronger function of time, in the low frequency range, than Z^{-1} -- the reverse of the conclusion which would be drawn from an L^2-L^4 G-L model.

References

1. J. S. Koehler, Imperfections in Nearly Perfect Crystals, (John Wiley and Sons, Inc., New York, 1952), p. 197.

2. A. Granato and K. Lucke, J. Appl. Phys. 27, 583 (1956).

3. D. O. Thompson, O. Buck, R. S. Barnes, and H. B. Huntington, J. Appl. Phys. 38, 3051 (1967).

4. A. Sosin and D. W. Keefer in Microplasticity, edited by C. J. McMahon, Jr., (John Wiley and Sons, New York, 1968).

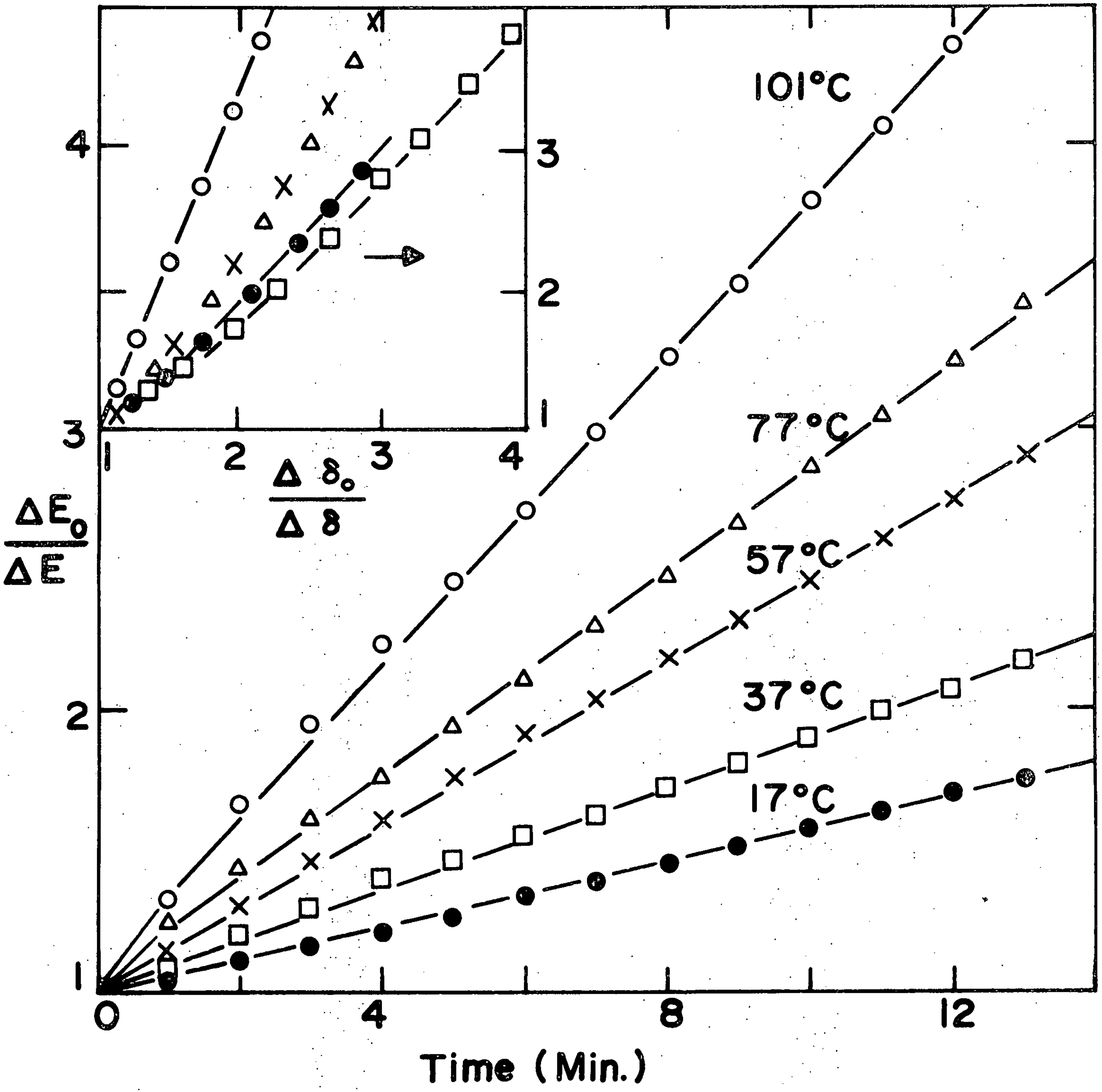
5. D. W. Keefer has reanalyzed data reported in gold for irradiation at 20°K and he finds that Y is proportional to Z to $Y^{-1} = Z^{-1} = 7$. For the original work see D. W. Keefer, J. C. Robinson, and A. Sosin, Acta Met. 14, 1409 (1966).

Figure Captions

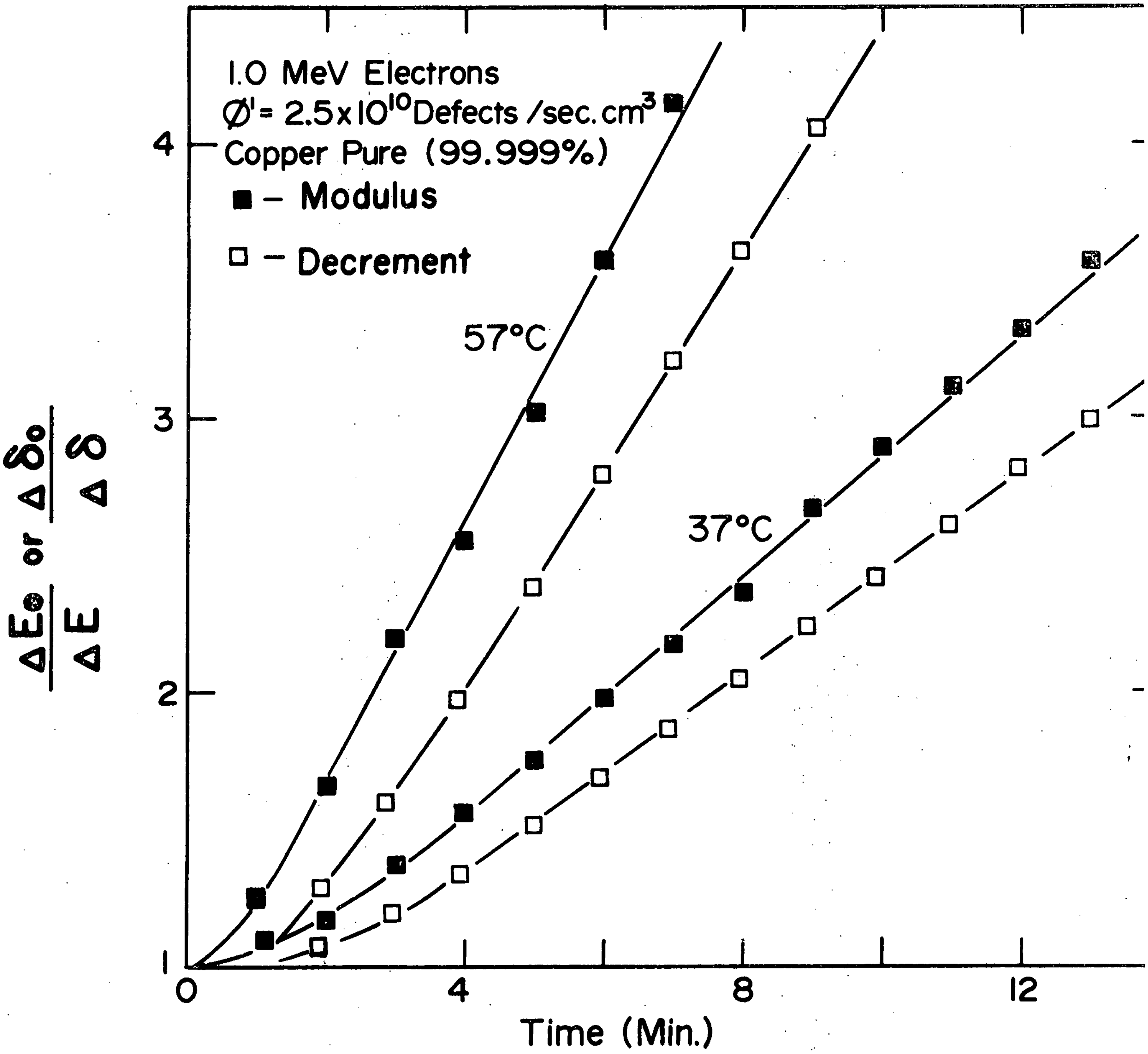
Figure 1. The normalized inverse modulus defect plotted as a function of time for the indicated temperatures. The sample material was copper (99.9%) and the production rate was 2.5×10^{10} defects/sec. cm^3. The inset shows a plot of the normalized inverse modulus defect versus the normalized inverse decrement.

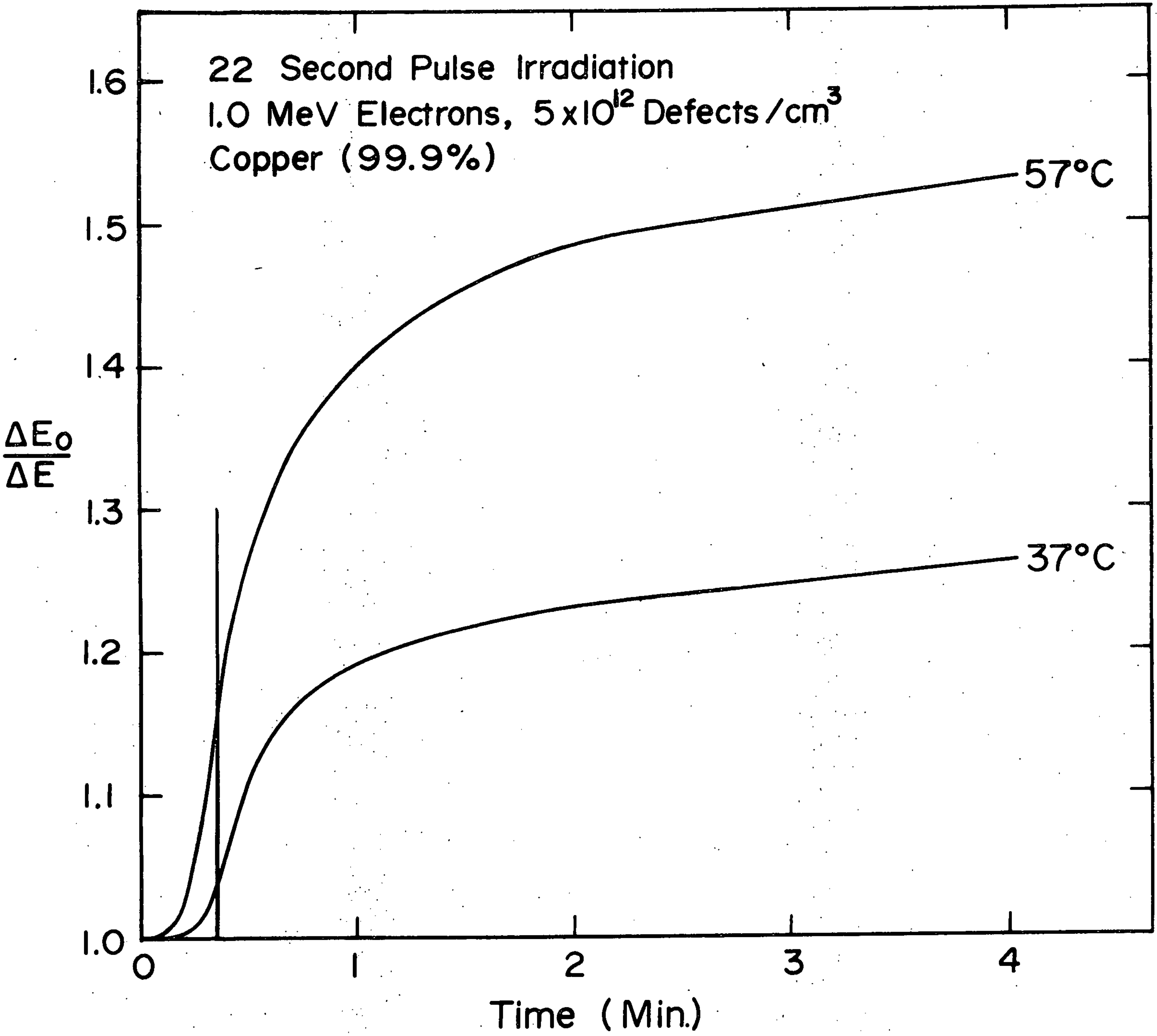
Figure 2. The normalized inverse modulus defect and decrement plotted as a function of time for the indicated temperatures.

Figure 3. The normalized inverse modulus defect plotted as a function of time for the indicated temperatures. The vertical line at 22 seconds indicates the end of the pulse irradiation.



101°C
77°C
57°C
37°C
17°C
$\frac{\Delta E_0}{\Delta E}$
1
2
3
4
0
4
8
12
Time (Min.)
$\frac{\Delta \delta_0}{\Delta \delta}$
1
2
3
4
1
2
3


1.0 MeV Electrons
Ø' = 2.5 x 10^10 Defects /sec. cm^3
Copper Pure (99.999%)
■ – Modulus
□ – Decrement
57°C
37°C
ΔE₀/ΔE or Δδ₀/Δδ
Time (Min.)
0
4
8
12
1
2
3
4


22 Second Pulse Irradiation
1.0 MeV Electrons, 5 x 10^12 Defects / cm^3
Copper (99.9%)
57°C
37°C
ΔE0 / ΔE
1.0
1.1
1.2
1.3
1.4
1.5
1.6
0
1
2
3
4
Time (Min.)