Reply to "Comment on 'Free Migration of Interstitials in Tungsten'"

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The argument by Seidman, Wilson, and Nielsen concerning our recent Letter is shown to be not decisive. We now propose that the defects associated with the 27-K internal-friction peak, in neutron-irradiated W may be di-interstitials.

This Comment includes a reply to the Comment by Seidman, Wilson, and Nielsen[1] and some alterations to our recent Letter.[2]

The cases where dislocation pinning does not imply a long-range migration of point defects to dislocations would be as follows: (1) Point defects on the dislocation line rearrange themselves on the line so that the free length of the dislocation is reduced; (2) the pinning occurs through a Snoek ordering of point defects in the dislocation stress field (Snoek pinning); and (3) only the point defects close to dislocation lines are attracted to the dislocations through their stress field. Concerning the dislocation pinning at ~15 K observed in our recent internal-friction experiments on W single crystals,[2] good coincidence between the temperature of recovery of the Snoek peak due to interstitials and that of the dislocation pinning eliminates the possibility of cases (1) and (3). A rough estimate of the activation energy for this pinning process gives a value too small for Snoek pinning due to the defects related to the 27-K peak, so case (2) does not seem probable. And further, the amount of change in the modulus defect during the recovery at about 15 K relative to that during irradiation is reasonable for pinning due to free migration of interstitials, as compared with that observed in the well-established stage I of Cu.[3,4] This will be described in the publication giving full account of Ref. 2.

Therefore, the results of dislocation-pinning measurements seem to provide fairly strong evidence of the free migration of interstitials in substage I_1 (~15 K). If there are any recovery stages at higher temperatures which are due to the defects of an interstitial type, it would be natural to associate them with interstitials of a different type, or interstitials trapped by either other interstitials or impurity atoms. For this reason, the interstitials appearing at the specimen surface at ~38 K in the field-ion-microscope (FIM) experiments by Scanlan, Styris, and Seidman[5] were suggested to be interstitials trapped by impurities. Also there surely is the possibility of the interstitials being trapped by other interstitials. Our reason for suggesting these impurities is that the high value of the residual-resistivity ratio (RRR) may not necessarily exclude the possibility of impurity trapping. There seems to be no evidence which excludes the impurities which contribute much less to the RRR than usually considered. Furthermore, there is the possibility that the irradiation may increase the dissolved impurity concentration through dispersion of the clustered impurities which would have been present in the specimen and contributed much less to the RRR before the irradiation. However, if their specimens are so pure as to exclude the possibility of the impurity trapping, the interstitials observed at 38 K would be those trapped by other interstitials.

In their very recent work,[6] Wilson and Seidman show that the imaging electric field may lower the recovery temperature up to ~10 K. With this temperature shift, the substage I_1 has already been completed before the FIM observation if the observation is started at ~18 K. Even when the observation starts at 6 K, the substage I_1 will be half completed. It is thus possible that the free migration of interstitials is not observable in an FIM experiment. Then the conflict between their results and the present model is that they could not observe the substage I_2 (~28 K) which, if their estimation of the maximum temperature shift is correct, should have been observed at 18–28 K in FIM experiments. We may, however, suggest that their estimate of the temperature shift based on comparison between the irradiations at 18 and 50 K would be somewhat uncertain. First, because of the difference in defect concentration during the irradiation cluster formation would be different between these two, and direct comparison is thus not proper. Second, in spite of the irradiation at 50 K, there appears to be some recovery below 50 K starting at ~30 K. If a temperature shift of ~ 20 K due to the imaging electric field is assumed, the conflict would almost disappear.[7]

In conclusion, whereas the comments be Seidman, Wilson, and Nielsen[1] brought up some difficulty with our proposal of free migration of interstitials at 15 K in W, the issue seems not yet decided, and their results could be reconciled with our proposed model.

In line with the greater importance that di-interstitials seem to play, we have revised our interpretation of the 27-K peak. In Ref. 2, the 27-K peak was considered to correspond with the peak by DiCarlo, Snead, and Goland[8] at 30 K. Good agreement in a peak height expected from the Frenkel-pair concentration between neutron and electron irradiations had led us to discard the possibility of di-interstitials as the defects responsible for the 27-K peak; these defects were considered to be the interstitials trapped by impurity atoms. However, close examination of the results, including those of impure specimens, indicates that the peak reported by DiCarlo, Snead, and Goland at 30 K does not correspond with the 27-K peak in the present experiment, but possibly with the 30-K peak, which appears half buried in the 27-K peak in the pure single-crystal specimen. Therefore, the defects responsible for 27-K peak are more likely to be di-interstitials. In the neutron irradiation, the high-energy primary knock-on atom produces a cascade where the local defect density is sufficiently high to give a large chance for the interstitials to form di-interstitials. Since the locally high defect density in the cascades remains almost the same as the irradiation dose increases; so long as overlap of the cascades does not occur, the number of di-interstitials and also the 27-K peak height increase linearly with irradiation dose. On the other hand, since DiCarlo, Snead, and Goland irradiated the specimen with electrons at 20 K where the free interstitials were mobile and the formation of di-interstitials was scarce, they could not observe the large 27-K peak. A detailed account will be published elsewhere.

[1]D. N. Seidman, K. L. Wilson, and C. H. Nielsen, preceding Comment [Phys. Rev. Lett. 35, 1041 (1975)].

[2]S. Okuda and H. Mizubayashi, Phys. Rev. Lett. 34, 815 (1975). In lines 21–22, left-hand column, page 815, (nominal purity 99.99%) should read (nominal purity 99.999%).

[3]D. O. Thompson, T. H. Blewitt, and D. K. Holmes, J. Appl. Phys. 28, 742 (1957).

[4]D. W. Keefer, J. C. Robinson, and A. Sosin, Acta Metall. 13, 1135 (1965).

[5]R. M. Scanlan, D. L. Styris, and D. N. Seidman, Philos. Mag. 23, 1439, 1459 (1971).

[6]K. L. Wilson and D. N. Seidman, Cornell University Materials Science Center Report No. 2346, 1974 (unpublished).

[7]Here, we have taken seriously their statement that essentially no change at 6–18 K was observed in FIM experiments. If we take only their results of annealing above 15 K, reconcilation of their results with ours seems possible by a temperature adjustment of less than a few degrees.

[8]J. A. DiCarlo, C. L. Snead, Jr., and A. N. Goland, Phys. Rev. 178, 1059 (1969).

Correlation Energy and Effective Mass of Electrons in an Inversion Layer

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I have calculated the correlation energy and effective mass of electrons in a two-dimensional electron gas. The results on the effective mass show good agreement with experiments on Si. However, when the finite thickness of the inversion layer is taken into account the effective mass is reduced. The difference between our results and those recently published by Ting *et al.* is due to their use of an approximation to the Dyson equation. Dispersion in the insulator and a finite insulator thickness have been considered.

The possibility of studying many-body effects on an electron gas in the inversion layer of a metal-insulator-semiconductor structure has been recognized for some years. The g factor has been measured by Fang and Stiles[1] and the effective mass for motion parallel to the surface was