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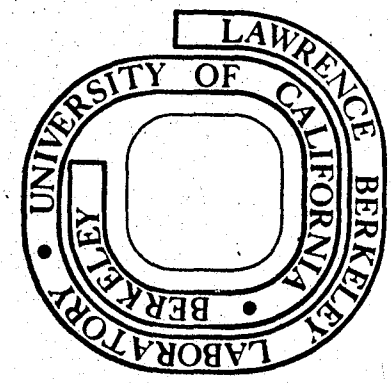

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ABSTRACT

Resolvable interstitial Frank loops were grown in (110) foils of high purity copper in the HVEM. At 575°K loops were grown at accelerating voltages as low as 275 kV, corresponding to an energy transfer of 12 eV. The considerable reduction in threshold energy from values[1,3] measured at room temperature or below (e.g. 18-20 eV) is thought to be related to thermally activated escape from correlated recombination[2].

INTRODUCTION

Traditionally the minimum energy required to produce stable Frenkel pairs, E_d, has been measured at room temperature or below where a value of 18 to 20 eV is found in copper. Results presented here indicate that E_d decreases to 12 eV at 575°K.

With respect to the temperature dependence of the threshold energy there are two conceptually separate processes of importance. That is, actual Frenkel pair production, and the possibility of subsequent correlated recombination.

The damage mechanism of Frenkel pair production at low energies is generally assumed to be that of focussed replacement collisions (FRC). Thermal vibrations will tend to defocuss FRC's and hence can only account for an increase in E_d. From Thompson's analytical expression for E_d[4] [$E_d = (A/2 \exp(-D/2b)]$ where A and b are the coefficients of the Born-Mayer potential and D is the lattice plane spacing) it is seen that the effects of increasing temperature on the lattice parameter and elastic constants will result in a lower displacement energy via the FRC displacement mechanism.

The temperature dependence of the probability that Frenkel pairs will suffer correlated recombination arises from the ability of thermal vibrations to separate closely spaced vacancies and interstitials that would anihilate otherwise[2]. Hence less energy is required from the electron-atom collision to produce freely migrating point defects.

The potential importance of small changes in E_d is illustrated by the fact that for 650 kV electron irradiation of copper a reduction of E_d from 20 to 12 eV increases the displacement damage rate by 240%.

EXPERIMENTAL

Electron irradiations were performed in a Hu-650 kV electron microscope on 99.999% (MRC) copper. Irradiations were performed at 475 and 575°K at accelerating voltages between 650 and 275 kV. To measure E_d a fully focussed beam was used (2-3 amps/cm^2) to determine if Frank dislocation loops could be nucleated and grown in a time of 30 minutes. All irradiations were performed along the <110> direction.

RESULTS

E_d was determined at 475 and 575°K and in both cases was found to be well below the room temperature value (see fig. 1). At 575°K the dislocation loop growth rate (G) was measured as the accelerating voltage was decreased from 325 to 275 kV (see fig. 2). The value of G was found to decrease sharply over this range of accelerating voltage.

DISCUSSION

Experimental evidence presented here indicates that E_d may be temperature dependent. But before going further one must consider if subthreshold displacement damage is present in significant quantitites to give erroneous results for E_d.

It has been proposed by Bauer and Sosin[5] that a probable cause of subthreshold damage may be light impurity atoms since they can absorb more momentum from the incident electrons than the heavier copper atoms. When a displaced impurity atom collides with a solvent atom more momentum may be imparted to it than in a direct electron-copper atom collision.

To avoid this type of displacement damage, great care was taken to maintain the high purity of the initially 99.999% copper. After electropolishing the thin foils were outgassed at 1000°K in the HVEM vacuum

(10^{-5} torr). Following this treatment damage was still observed at 275 kV and 575°K.

The calculation of the damage cross section for the two stage impurity displacement mechanism, σ_{imp}, lends further proof that this type of damage is not present in our experiments. The total cross section has been plotted in fig. 2. Here it is seen that for hydrogen as the impurity the cross section is relatively constant over the range of accelerating voltage from 275 to 325 kV. The dislocation loop growth rate is varying markedly over this same energy range, hence it is unlikely that the displacements occur by the impurity mechanism. In addition the magnitude of σ_{imp} is too small to account for the observed damage rate. We estimate the observed damage cross section at 275 kV and 575°K to be about .5 barns. σ_{imp} for hydrogen at 275 kV is about (1 barn)·(concentration of H), hence a concentration of 50% H is required to account for the observed damage, clearly an unreasonable value. The explanation for the small value of σ_{imp} lies in the fact that a hydrogen atom must have 330 eV to be able to transfer 20 eV to a Cu atom.

The proposed subthreshold damage mechanism has been shown to be incapable of producing the experimentally observed displacement damage. Hence it is concluded that in the present study growth of Frank dislocation loops arises from atomic displacements as a result of normal electron-copper atom collisions. The explanation for how such low energy collisions can result in atomic displacements is most likely related to the temperature at which the experiment was conducted.

Roth et al.[2] have proposed an explanation for the temperature dependence of E_d based on the idea of thermally activated escape of point

defects from correlated recombination. If Frenkel pairs that are separated to a sufficient distance where spontaneous recombination does not occur (2 or 3 atomic spacings) but correlated recombination, via diffusion, of the point defects is still dominant then an increase in thermal energy can aid in increasing the fraction of Frenkel pairs that manage to escape correlated recombination. The process of spontaneous recombination cannot be effected by thermal vibrations since it occurs in a time interval shorter than that of thermal oscillations. According to the above discussion one would expect E_d to decrease with increasing temperature although this effect would reach saturation when the limit imposed by spontaneous recombination is reached.

The lattice parameter and elastic constant change by about .5 and 20 percent respectively in copper for an increase from room temperature to 600°K From consideration of the previously mentioned analytical expression for E_d resulting from FRC's these temperature induced changes in material properties should result in a smoothly decreasing value of E_d as temperature is increased.

Sosin[6] has pointed out that thermal vibrations may increase the efficiency of momentum transfer between the incident electrons and atoms if the thermal velocity is aligned with the displacement direction at the time of collisuon. However, E_d will only decrease by about 2 eV due to this effect.

The qualitative predictions made for the temperature dependencies of the displacement and recombination mechanisms mentioned above are consistant with the experimental observed decrease in E_d. To gain more insight about this complicated situation a quantitative study of E_d over

a wider range of temperature would be valuable.

CONCLUSIONS

The significant reduction in the measured value of E_d can be confidently attributed to a temperature dependent displacement energy threshold rather than to the impurity related subthreshold damage mechanisms. The origin of this temperature dependence is, however, not as certain. Thermally activated escape from correlated recombination seems the most likely explanation of this temperature dependence, but the effects of the temperature dependence of the lattice spacing and the elastic constants on the process of focussed replacement collisions may also be important.

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