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ABSTRACT

During electron irradiation at low energies which results in a negligible damage rate in a pure material, lighter solute atoms are displaced, which may in turn indirectly displace solvent atoms by a focussed replacement collision or an interstitial diffusion jump. The extent to which lighter solute atoms contribute to the subthreshold damage rate has been examined by irradiating copper-aluminum alloys at high temperatures in a high voltage electron microscope. The damage rate, as measured by monitoring the growth rate of dislocation loops, at 300 kV was found to increase linearly with the aluminum concentration.

INTRODUCTION

When high energy electrons collide with atoms the kinetic energy transfer is very inefficient due to the large differences in mass of the two particles involved. Hence, E_c, the minimum electron energy required such that the displacement energy, E_d, can be transferred to the atoms, in orders of magnitude larger than E_d.

As a result of this a binary alloy undergoing electron irradiation will exhibit two important regions of incident electron energy; they are bounded by being above and between the values of E_c for both atomic species and will be called the above-threshold and selective knock-on regions respectively. The term selective knock-on (SKO) is used to indicate that in this energy region only the lighter atomic species can absorb enough energy from the incident electrons to result in displacements. In the above-threshold region (AT) both atomic species will suffer displacing collisions with electrons.

For electron irradiation of a copper-aluminum alloy at 10°K the boundary between the two regions of accelerating voltage is 390kV, corresponding to the value of E_c for Cu.

Many investigators[1,2] have proposed that the presence of light impurity atoms might be the cause of subthreshold damage (e.g. anomalously low energy displacements) since light impurities can absorb sufficient kinetic energy from the low energy incident electrons to initiate displacements while the heavier solvent atoms can not. In this investigation a quantitative look is taken at the contribution light solute atoms may make the low energy damage rate by studying Cu/Al alloys.

EXPERIMENTAL PROCEDURE

Electron irradiations at 300 and 575 kV were performed on three Cu/Al alloys (2, 6.8 and 15 at% Al) in a HU-650 high voltage electron microscope at 350°C. All irradiation were aligned with the <110> crystallographic direction. Dislocation loop growth rates were measured by taking sequential micrographs.

RESULTS

To determine the damage cross section (σ) the damage rate (K) must be known. Unfortunately K is not directly measureable in the HVEM. This difficulty can be overcome by using the following procedure: First consider that G is equal to some unknown function of K. Therefore: G = f (K) but $K = \sigma . \phi$ where ϕ = electron flux, therefore $G = f(\phi . \sigma)$. If two irradiations are performed, one in the AT region and the other in the selective knock-on region, while the respective electron fluxes are adjusted to result in equal values of G, then the following ratio can be written:

$$1 = \frac{G(AT)}{G(SRO)} = \frac{f(\phi_{AT} \sigma_{alloy})\ (AT)}{f(\phi_{SKO} \sigma_{alloy})\ (SKO)} \quad (1)$$

It follows that if the two growth rates are equal than the arguments of the two functions must be equal as well. Therefore:

$$\frac{\phi_{AT}}{\phi_{SRO}} = \frac{\sigma_{alloy\ (SKO)}}{\sigma_{alloy\ (AT)}} \quad (2)$$

The left side of this equation can be determined experimentally and serves as a check for the validity of the theoretical cross section. From equation (2) it is seen that the ratio of these electron fluxes will equal the inverse ratio of their respective damage cross sections. This is plotted in fig. 1 against the solute concentration for the three alloys studied. An approximately linear relationship between the ratio of the cross section and the Al concentration is found.

DISCUSSION

To arrive at a theoretical value of the damage cross section for a Cu/Al alloy, we use the following expression:

$$\sigma_{alloy} = X_{Al}\sigma_{Al} + X_{Cu}\sigma_{Cu} \quad (3)$$

where X is the mole fraction. In general it is necessary to know the value of E_d to be able to calculate $_{alloy}$. E_d is not precisely known in alloys; however, this is of little consequence since it is found that the value of the ratio in equation (2) is insensitive to the value of E_d, provided that proper AT and SKO voltages are chosen. It is for this reason that accelerating voltages of 300 and 575 kV were used in this experiment. The ratio of the AT to SKO cross section for the alloy can be written as follows:

$$\frac{\phi_{SKO}}{\phi_{AT}} = \frac{(X_{Al}\ \sigma_{Al} + X_{Cu}\ \sigma_{Cu})_{AT}}{(X_{Al}\sigma_{Al} + X_{Cu}\ \sigma_{Cu})_{SKO}} \quad (4)$$

But $\sigma_{Cu(SKO)} = 0$ and $\sigma_{Al(AT)} \approx \sigma_{Cu(AT)}$ for the AT voltage used here, therefore:

$$\frac{\phi_{SKO}}{\phi_{AT}} = X_{Al}\ \frac{\sigma_{Cu(AT)}}{\sigma_{Al(SKO)}} \quad (5)$$

It is seen that theory predicts a linear relationship between the ratio of the cross section and the Al concentration. This was found experimentally.

CONCLUSIONS

It is concluded that Al atoms are responsible for the significant damage rates observed during 300 kV irradiation of the Cu/Al alloys. Since equation (5) was confirmed experimentally, it is verified that in the present case the light solute atoms facilitate displacements by their increased efficiency of momentum transfer from the incident electrons.

However, this conclusion cannot be extended to very light impurities such as hydrogen since the inefficiency of momentum transfer between the impurity and solvent atoms becomes the dominant factor. A hydrogen atom must possess about 300 eV to be able to transfer 20 eV to a copper atom. Hence the effective values of E_d for the SKO damage mechanism involving hydrogen is 300 eV which yeild a negligibly small value for $\sigma_{hydrogen}$.

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