N72-10063

THE OBSERVATION OF STRUCTURAL DEFECTS IN NEUTRON-IRRADIATED LITHIUM-DOPED SILICON SOLAR CELLS

G. A. Sargent
Department of Metallurgical Engineering and Materials Science
University of Kentucky
Lexington, Kentucky

ABSTRACT

Electron microscopy has been used as a technique to observe the distribution and morphology of lattice defects introduced into lithium-doped silicon solar cells by neutron irradiation. Upon etching the surface of the solar cells after irradiation, crater-like defects are observed that are thought to be associated with the space charge region around vacancy clusters. The crater defect density was found to increase with increasing irradiation dose and increasing lithium content; however, the defect size was found to decrease with increasing dose and lithium.

Thermal annealing experiments showed that the crater defects were stable in the temperature range 300 to 1200 K in all of the lithium-doped samples. Some annealing of the crater defects was observed to occur in the undoped cells which were irradiated at the lowest doses.

I. INTRODUCTION

It is now generally accepted that a localized cluster of lattice defects may be produced by a recoil from a single collision between an energetic neutron and a lattice ion (Refs. 1-5). The energy of the recoil is dissipated by creating lattice disorder. Subsequent rapid quenching of the lattice should freeze a large concentration of lattice defects into the neighborhood.

Until recently, the behavior of irradiated semiconductors has been interpreted on the basis of isolated Frenkel defects in terms of the model of James and Lark-Horovitz (Ref. 6). However, Gossick (Ref. 7) and Crawford and Cleland (Ref. 8) have proposed a model of disordered regions that is more applicable to neutron-irradiated semiconductors and predicts the existence of regions of highly localized damage. Their model assumes that a region of lattice disorder is produced upon irradiation which may contain a high concentration of defects such as vacancies. Surrounding the disordered region is a potential well that arises because the position of the Fermi level relative to the energy band is different within the disordered region compared to that outside. Crawford and Cleland have estimated the size of the defect region to be of the order of 15 to 20 nm. For P-type silicon the dimensions of the space-change region surrounding the defect region due to the potential well is predicted to be about 200 to 250 nm in diameter.

The measurement of electrical properties by Closser (Ref. 9) and Stein (Refs. 10-12) have subsequently provided direct evidence for the existence of damage regions as predicted by the theoretical models of Gossick and Crawford and Cleland.

Until recently little work has been carried out to determine the exact structural nature of the lattice disorder created by irradiation damage. X-ray diffraction (Ref. 13) techniques and direct observation of thin foils by electron microscopy (Refs. 14-16) met with limited success in this respect. However, an alternative method for observing defects in semiconductors using surface replication electron microscopy has been perfected by Bertolotti and his coworkers (Refs. 17-20).

Bertolotti found that upon etching the surface of neutron-irradiated silicon samples craters were produced, the dimensions of which were found to compare with the dimensions of the space-charge regions as predicted by the theory of Gossick (Ref. 7) and Crawford and Cleland (Ref. 8). Within the craters a small well-defined region could also be observed, the size of which compared well with the theoretical estimates for the size of the defect clusters.

The main objective of the work to be described in this present paper was to make use of the technique developed by Bertolotti to determine the effects of neutron irradiation on the structural characteristics of undoped and lithium-doped silicon solar cells. The overall objective was to obtain a better understanding of the morphology of the defects produced by irradiation damage and their interaction with dopants such as lithium. Such knowledge could lead to the development of solar cells which are more radiation resistant.

II. EXPERIMENTAL TECHNIQUE

The work was carried out on commercial undoped and lithium-doped silicon solar cells prepared by Heliotek. The cells were produced from float-zone melted single crystals of phosphorus-doped N-type silicon. Boron was diffused into the slice to give a junction depth of 0.5 μm. Lithium was diffused in using the paint-on technique to produce three types of cells: 10^{15}, 10^{16} and 10^{17} lithium atoms/cm^3. In addition, a fourth type of cell was produced with no lithium.

Samples of the undoped and lithium-doped cells were irradiated with monoenergetic 14.7-eV neutrons produced by a Cockroft-Walton generator. The irradiation was carried out at room temperature, and the dose was controlled by varying the distance of the samples from the target.

After irradiation the surface of the solar cells was prepared for replication by mechanically grinding and polishing and then by etching with CP4A etchant. A carbon replica of the surface was obtained by evaporation. The replica was shadowed with chromium and was observed in an electron microscope at 75 kV.

To study the recovery of the irradiation damage a number of samples were annealed at temperatures of 293, 593, 700, 900 and 1200 K for 10 min in a vacuum furnace (10^{-6} torr).

III. RESULTS AND DISCUSSION

Figure 1 shows a photograph obtained in the electron microscope of a surface replica taken from the etched surface of an unirradiated sample which contained no lithium. This photograph shows a finely etched uniform structure without any additional significant features. In contrast, Fig. 2 shows a surface replica from a sample which contained no lithium but was irradiated with 10^{11} neutrons/cm^2. This is a typical example of the appearance of the etched surfaces of the samples after neutron irradiation. The area shows a finely etched background structure on which many crater-like depressions can be observed.

According to the Gossick theory (Ref. 7), the dimensions of the craters revealed by the above techniques actually correspond to the size of the space-charge region which surrounds a cluster of lattice defects formed during the irradiation. Therefore, the density of the craters should relate to the total defect volume produced at a given irradiation dose.

The average density and diameter of the craters were measured as a function of dose and lithium content. Values of the average crater defect density and diameter as functions of irradiation dose and lithium content are presented in Figs. 3 and 4, respectively. It can be seen that the average defect density increases with increasing irradiation dose and increasing lithium content. On the other hand, however, it can be seen from Fig. 4 that the average defect diameter decreases with increasing dose and lithium content. It was found from these results that, for a given irradiation dose, the total defect volume is essentially constant. It appears that the presence of lithium provides more nucleation sites for the defect clusters to form, and as a result the average defect diameter is smaller. Under comparable irradiation conditions, 14.7-MeV neutrons at a dose of 10^{12}/cm^2, the present results are in good agreement with those reported by Bertolotti, et al., (Ref. 19). Therefore, the present results support the theories of Gossick (Ref. 7) and Crawford and Cleland (Ref. 8).

From the annealing experiments it was found that no change could be detected in either the average defect density or the average size over the temperature range 300 to 1200 K, with the exception of those samples which were undoped and irradiated at the two lowest doses, i.e., 10^{10} and 10^{11} n/cm^2. These results are shown in Figs. 5 and 6 where the average defect density and size are plotted, respectively, as a function of annealing temperature. In these samples annealing was found to be significant at a temperature of about 800 K and was reflected in both an increase in defect density and a decrease in defect diameter.

It would appear from these results, therefore, that the defect structure which is formed during the irradiation at room temperature of either the undoped or doped material, at the highest doses, represents the most stable defect structure. The large defect clusters which are formed at the low doses in the undoped material have a tendency to collapse upon annealing to form smaller defects at a higher density.

The results of the annealing experiments carried out in the present work appear to be significantly different from those observed previously from recovery of electrical properties in neutron irradiated silicon, by Stein (Ref. 21) and Passenheim and Naber (Ref. 22). However, it is not possible at the present time to make direct correlation with these results as the irradiation conditions and annealing times were significantly different.

It is not apparent from the present results exactly what role lithium plays in the nucleation and stabilization of the irradiation-induced defects. At the high temperatures used in the annealing experiments it is unlikely that lithium would remain in the bulk lattice. There is some evidence (Refs. 23, 24), however, that at the temperature at which the irradiation is carried out the irradiation-induced defects are trapped at precipitated metallic lithium and form stable clusters. The subsequent annealing of the defect cluster, once it has reached a stable configuration or critical size, could be quite independent of the presence of lithium. Hence, the presence or mobility of lithium at the higher annealing temperature would not necessarily influence the annealing kinetics of the defect clusters.

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Fig. 1. Surface replica of an undoped and unirradiated solar cell

Fig. 2. Surface replica of an undoped solar cell irradiated with 10^{11} neutrons/cm^2

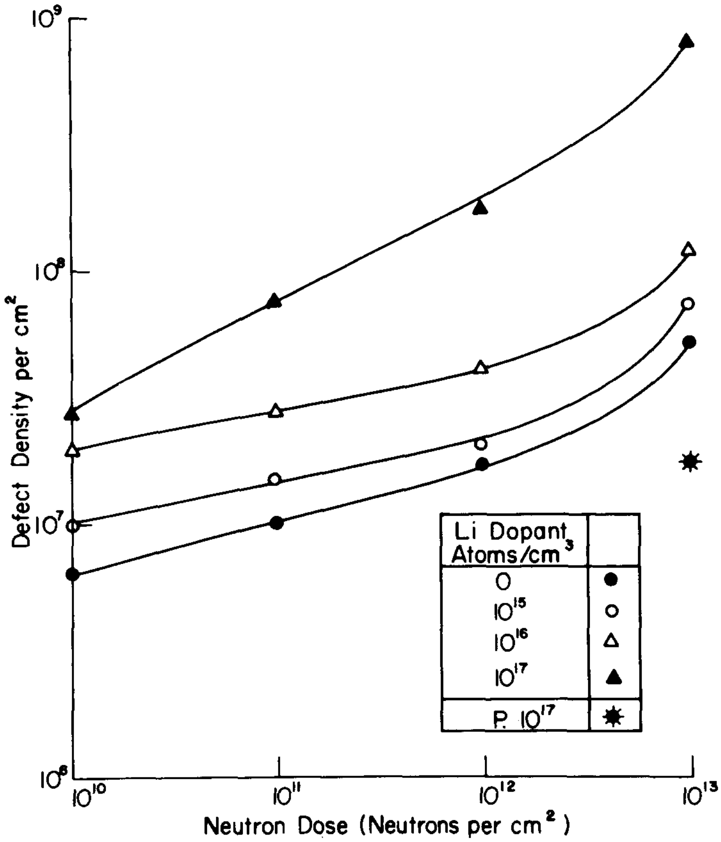

Fig. 3. Average defect density as a function of irradiation dose and lithium dopant

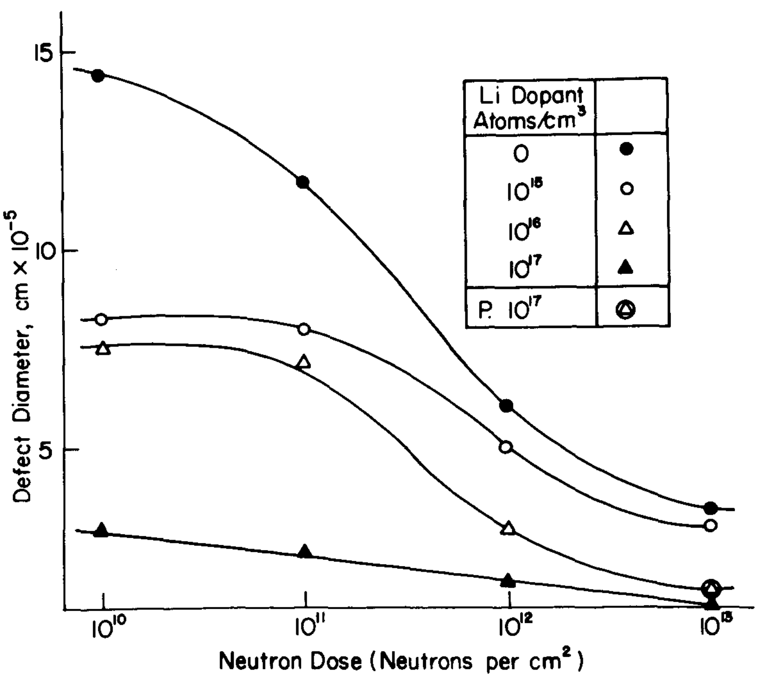

Fig. 4. Average defect diameter as a function of neutron dose and lithium dopant

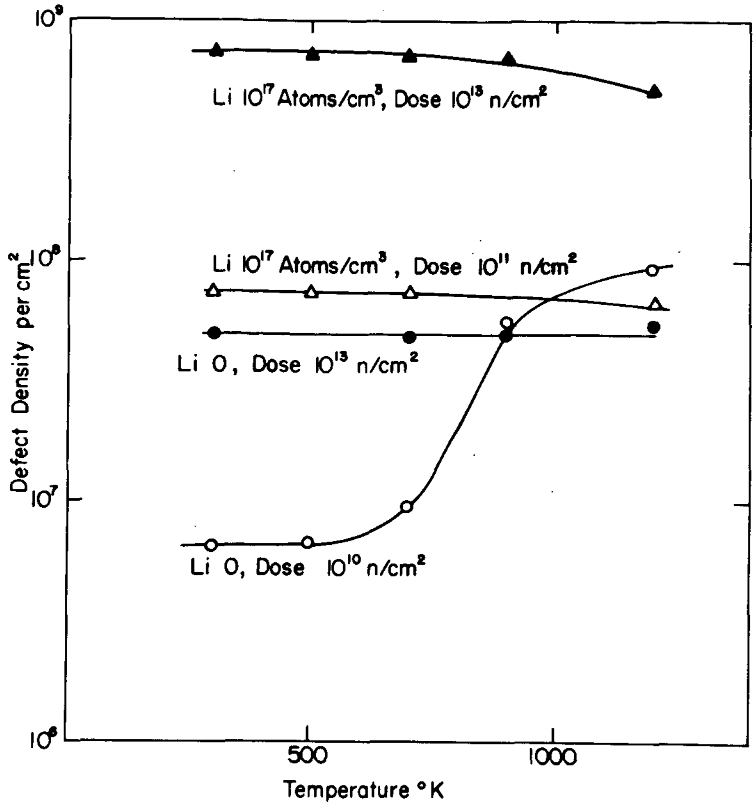

Fig. 5. Effect of thermal annealing on defect density

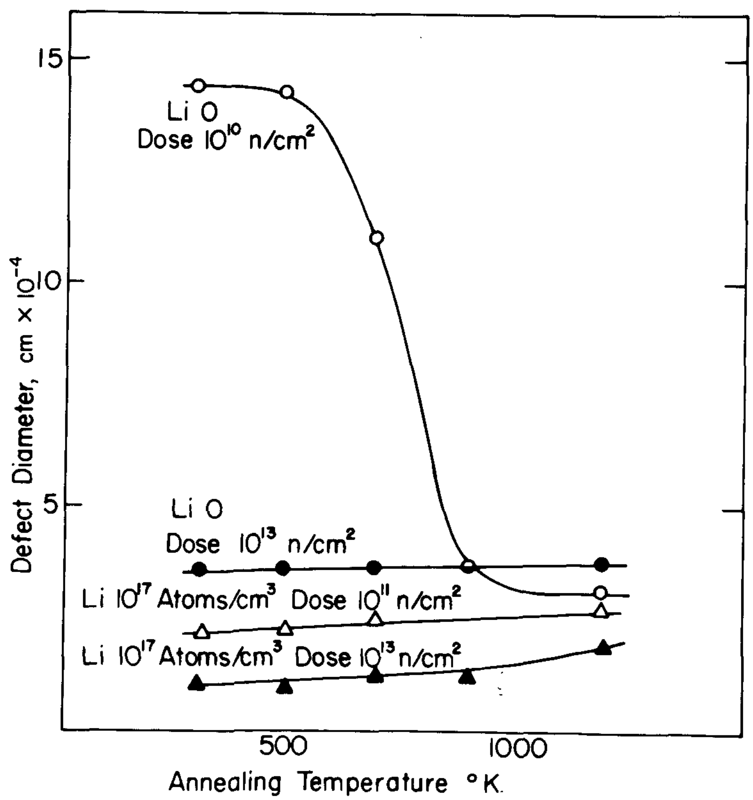

Fig. 6. Effect of thermal annealing on defect diameter