Radiation Damage in Semiconductors

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Abstract

When a high-energy particle transverses the lattice of a crystalline solid, it looses energy by several processes introducing lattice imperfections. Such impurities may have important influences on the properties of a solid that has been exposed to high energy radiation. A short review on the fundamentals and classification of the processes envolved is presented. The influences on the properties of semiconductors is also briefly discussed focusing on the Solid State aspects as opposed to detector maintaning aspects.

1 Qualitative Discussion of Damage Events

Let's consider a high-energy particle transversing the lattice of a crystalline solid. Events of many different natures may take place. For example, it may itself become lodged in the lattice. It is very important to consider such a case for proton, deuteron or alpha incident particles. Also it may produce a nuclear reaction which is usually an important factor when considering reactor irradiations. These efects are refered to as *chemical impurities*.

The damage events we will be concerned with result from an incident high-energy particle hitting the nucleus of an atom of the material being irradiated. In the case of electron and charged heavy-particles, e.g., protons, deuterons, alphas, the coulomb potential governs the dynamics of the particle-nucleus collision. In the case of neutrons, the short-range nuclear forces govern. In the case of gammas, the dominant displacement interaction is via production of Compton electrons which then interact with the nucleus. All of these processes are well estabilished theoretically and experimentally. A great deal of the incident particle's energy can be transfered to the target nucleus. The average energy transmitted, however, is considerably lower than this maximum, particularly in the case of Coulomb interactions.

As a result of the particle-nucleus collision, energy is transfered to atom. The recoiling atom then interacts with its neighboring atoms. The corresponding interaction potential can be approximated by, for example, the Bohr screened Coulomb potential. With that assumption the interaction energy is considered to vary roughly exponentially versus interaction distance. Through the atom-atom collisions, energy is transfered from the primary recoil atom to the rest of the lattice. This excess of energy in the lattice immediately adjacent to the initial nuclear collision is sometimes characterized as a temperature and this region is termed a thermal spike.

If the energy of the primary recoil atom is relatively low, all that results is a local heating of the lattice. As the energy of the recoil atom gets higher, an energy is reached where the recoil atom is displaced to a (metastable) interstitial site, leaving a vacancy behind. This type of event is called displacement event, the corresponding energy called the threshold energy for displacement and the defects are refered to as *physical impurities*. The detail of the displacement process will depend on the energy of the recoil and its direction with respect to the other lattice atoms.

2 Classification of Defects

2.1 Point Defect

Point defects include lattice vacancies, interstitial atoms and chemical impurities. In the damage event described we have a single vacancy and a single interstitial. The specific location of the interstitial with respect to the vacancy is important. There is a number of sites where the interstitial can be located and be essentially bound to the vacancy via the distortions each one produces in the lattice. Such vacancy-interstitial pair is called close-pair or Frenkel pair. In certain materials, for a certain minimum separation, such complexes may have appreciable stability and may resist recombination. This defect is produced in specially appreciable yield by electron bombardmennt. Interstitials in other than close-pair sites are called free.

The simple interstitials or vacancies can migrate and agglomerate forming di-interstitials or di-vacancies. Di-interstitials and di-vacancies can also be directly introduced in the damage process. The high-energy recoil atom can impart sufficient energy to displace a secondary atom and still retain energy enough to get displaced. Indeed, as the primary recoil energy increases such higher-order damage processes become more likely.

2.2 Line Defect

The passage of a high-energy recoil atom through the lattice can also leave a whole trail of damage which is refered to as "spike" region or as "spike" damage or simply *line defect* (as opposed to *point defect*).

Vacancies which are produced by a recoil tend to be in a central core region with interstitials in the surrouding region. That configuration may collapse and form a disordered region called "displacement" spike. There are other aspects of a spike as well. For example, the core region of vacancies and surrrounding region of interstitials, when they do not collapse, still have different properties from the equivalent number of Frenkel pairs randomly distributed through the lattice. A high concentration of vacancy and interstitial within a small volume is specially important in radiation damage.

3 Influence of Lattice Imperfections on the Properties of Solids

3.1 Point Defect

The point defects just described disturbe the lattice arrengement so that the periodical electrical potential is disordered by several atomic distances. The change of the potential around the defect usually introduces localized eletronic states which are particularly important in non-metallic crystalls. In the following, some of the most important properties altered by the presence of point imperfections are discussed.

- Mechanical Properties: The presence interstitials or vacancies produces a change in density. The distortion of the lattice arrangement can be investigated by X-ray diffraction techniques such as line-shape analysis and lattice parameter measurements for large defect densities ($> 10^{-5}$ fractional concentration). As a result of the changes in the lattice spacing and interatomic binding, point defects also change the elastic behavior of solids. This is not to be confused with changes in the dislocation component of Young's modulus, which is also associated with point defects, but only through the interaction of these with line defects. The interactions between point defects and line defects affect the plastic behavior and are mentioned in a later section.

- Thermal Behavior: Point defects scatter phonons, therefore causing a decrease in thermal conductivity. Moreover, the presence of imperfections may also have a measurable influence on the specific heat of a solid. A special example of a thermal effect is stored energy which is released as heat when a specimen containing a high density of Frenkel defects is heated. An amount of heat equal to about 5 eV (the energy of formation) is stored in the lattice for each Frenkel pair, and recombination of the components of the defects releases this thermal energy.

- Electromagnetic Properties: Because the electric potential of the crystal is altered in their vicinity, point defects act as electron scattering centers and therefore increase the electrical resistivity in metals. Changes in resistivity have been extensively used for investigations of defects in metals, not because of the ease of fundamental interpretation of a change in this property, but rather because of the great ease of measurement.

- Localized Electronic States: The alteration of the crystal potential at the site of the defect usually results in the introduction of localized electronic states which, though of little importance in most metals, have extensive consequences in insulating crystals and most semiconductors.

3.2 Line Defect

From the standpoint of understanding the mechanical behavior of solids, the concept of line defect is by far the most important. This concept permits an understanding not only of the plastic deformation of solids and hence the magnitude of their tensile strength, but also of the phenomenon of crystall growth. In essence, a line defect is able to move under stress far below the yield stress of the perfect crystal. Its motion leads to platic deformation. A line defect can never end within the crystal. Either it follows a closed path or it extends to the surface. Every motion, even of parts of the line, results in deformation. The motion of a line defect is rectricted as motion in some planes may require diffusion of vacancies or interstitials. They induce elastic stress and thus interact with one another. This interaction can lead to dislocation rection, sometimes to complete anihilation. We see that the presence of a small number of line defects leads to a weakining of the crystal, while an appreciable increase in the number of dislocations can lead to stregthening. However the stregthening still does not approach that obtainable in a perfect crystal.

4 Semiconductors

Semiconductors such as germanium or silicon are widely used in radiation detectors. Besides their very good charge transport properties, the extensive experimental and theoretical investigations have led to a clear understanding of their nature (intrisic range) and also of their behavior after exposure to high-energy radiation (extrinsic range).

The prime characteristic of semiconductors is the variability over a wide range of charge-carrier concentration, either by virtue of impurity or defect content, or as a function of temperature. This is to be contrasted with metals in which the concentration of charge carriers is fixed and of the same order of magnitude as the density of atoms in the crystal.

In the intrinsic range, equal concentrations of electrons in the conduction band and holes in the valence band are produced by thermal ionization of atoms (valence bonds) or ions in the crystal. The type and concentration of charge carriers in the extrinsic range is determined by structural imperfections, either chemical or physical impurities. They form localized states in the forbiden energy gap which may occupied with electrons (donors) or just be vacant (acceptors). Manifestations of each are observed in a given material depending on its initial charge-carrier concentration and type (electron or hole conductor). However, whether the defects act predominantly as acceptors or donors depends on the material in question.

5 Conclusions

Defects produced by radiation are classified acording to the processes involved as point defect or line defect. Each kind of defect is associated not only to different radiation types, but also to the specific degradation of the characteristics of the solid. Defects produced by radiation alter important properties of solids not only at microscopical but also at macroscopical level.

The study of radiation damage in solids is carried out by investigating their structure-sensitive properties. In that way we learn not only about intrinsic characteristics of a solid but also about how to use radiation damaging as a technique for altering the properties of solids in a controled fashion.

The radiation-produced defects, whatever their actual description, have associated with them localized energy states which alter the concentration of charge carriers and mobility in a semiconductor. Many semiconductors are well understood and widely used in radiation detector being exposed to high energy incident particles. Their usefullness is therefore connected to a understanding of how the degradation of the desired characteristics happens and which further consequences it may have in the functioning of radiation detectors.

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