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Effect of Electron and Ultraviolet Radiations and Temperature on n-Si Conductivity

H. N. Yeritsyan,* A. A. Sahakyan,* S. K. Nikoghosyan,* V. V. Harutunyan,* S. Ohanyan,* and V. S. Avagyan*
Yerevan Physics Institute, Yerevan 0036, Armenia
and
V. A. Sahakyan † and K. A. Movsisyan†
Institute of Metrology, Yerevan 0051, Armenia

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In this paper the influence of space environment factors on the properties of silicon single crystals was studied. The investigations were carried out using the space environment simulator at Yerevan Physics Institute. In the present study silicon conductivity (the most important parameter for space application) measurements were carried out directly under the electron radiation (in situ measurements). It was found that the specific conductivity of silicon samples, measured during and after radiation, has different values; the first is much higher. The postradiation aging effect depending on storage time is also studied. The dynamics of radiation defect formation, decay, and silicon crystals recovery processes are examined.

Nomenclature

D = electron radiation fluence, el/cm^2
E = electron energy, MeV
L = size, mm
P = vacuum, torr
T = temperature, K
V = volume, m^3
σ = conductivity, Ohm$^{-1}\cdot$cm^{-1}

Introduction

STUDYING the influence of cosmic space high-energy particle radiation on properties of materials is difficult due to the wide spectrum and complex composition of the radiation. Therefore, it is necessary to analyze and select a certain type of radiation and materials most suitable for the application under certain conditions in outer space.

The papers published so far concerning the influence of radiation on the properties of solids deal with measurements performed before and after radiation, which provides information about postradiation properties of the samples only [1,2]. The works on studying the properties of solid states directly under the radiation process (in situ) are very scarce [3–6], however, these investigations have practical importance, for example, in space application.

The processes that occur in materials exposed to space radiation can be divided into two classes. The first type of processes are determined by the flux of the radiation or level of the radiation fluence and is characterized by ionization events in the material. These phenomena include radioluminescence, Cherenkov luminescence, leakage currents, and the generation of charge states on the surfaces of materials. These effects are transitory and disappear once the ionizing source is removed. The second group of processes depend on the radiation fluence and induces more permanent structural defects in materials. At room temperature these defects persist and thus affect the subsequent properties of the radiated materials.

Unambiguous interpretation of the results is further complicated by the fact that under the conditions which prevail in outer space, apart from ionizing radiation, there are other factors which influence the creation of structural defects in the sample materials. These factors include but are not limited to solar ultraviolet radiation, flows of various micrometeorite particles and ions, etc., which can cause photochemical or plasmochemical reactions on the surface of an object or induce formation of a mini-atmosphere.

It is impossible to incorporate all of these factors into a theoretical model, and so the problem should be addressed empirically by simulating the specified phenomena, selecting the most representative radiation and attendant conditions. Technically it is hard to entirely reproduce even the simultaneous effects of electron and proton radiations of desired intensities and fluences. Therefore, application of the concept of equivalent influence of various radiation types on the given material in a wide range of temperature, vacuum, thermocycling, etc., is necessary.

In processes where the formation of radiation structural defects is dominant, the choice of radiation should ensure that the type of defects and their spatial distribution is preserved. The charged particles interact with atoms in the material by means of long-distance Coulombic forces, resulting in frequent but weak collisions. In contrast, the neutral particles (those without charge) transfer large amount of energy when approaching atomic nucleus and the constituent atoms undergo infrequent, but energetic collisions. In the first process, the formation of large number of simple vacancy-interstitial type atoms predominates, while in the second case large disordered areas (clusters), consisting of hundreds of thousands of simple defects, are formed. The difference in these mechanisms results in different properties of the radiated materials, and it is very difficult to specify common equivalents for radiation by charged particles or for radiation by neutral particles. It is easier to find common features when comparing the effect of different charged particles on a particular material. For example, when modeling some effects in semiconductors it is reasonable to substitute protons and α-particles with an energy of several MeV, by electrons with energies of dozens of MeV. Nevertheless, each type of radiation-substitution requires its own particular and detailed analysis, because even when both kinds of radiation consist of charge particles, there is no absolute equivalence, because of different defect densities in the tracks of particles with different masses. To obtain reliable data, it is proposed to investigate the kinetics of radiation transformations as a function of time, the mechanisms by which the defects are produced, along

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*Number 2 Alikhanyan Bros. Street; grant@yerphi.am.
†Number 49/2 Komitas Avenue.

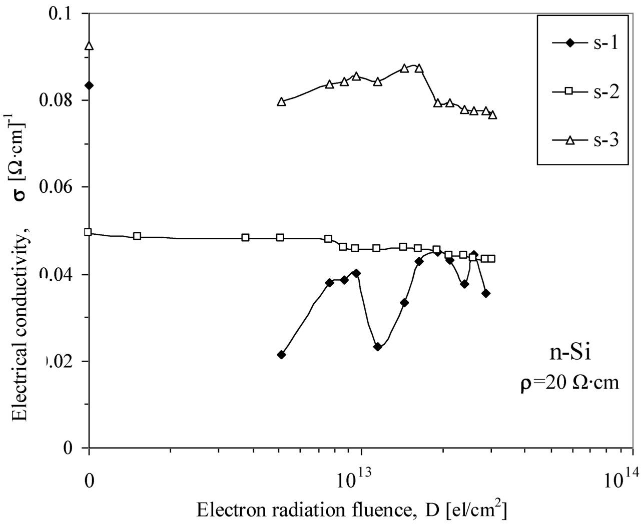

Fig. 1 Electron radiation influence dependence of conductivity $\sigma(D)$ for n-si: s-1: at UV excitation. Temperature of samples was 177K, vacuum $2 \cdot 10^{-5}$ Torr; s-2: at UV excitation. Temperature of samples was 290 K, in air; s-3: without UV excitation. Temperature of samples was 217 K.

Fig. 2 Near-Earth space conditions vacuum simulating chamber.

with their physical nature, temperature stability and attendant relaxation processes.

The aim of the current paper is to demonstrate the peculiarities of in situ study of the radiation influence on the properties of materials and create the necessary prerequisites for novel materials that are stable under ionizing and defect-inducing radiations, which may occur under different conditions of radiation-exposure in outer space.

Materials and Methods

The results of measurements with accuracy of about 5% are presented in Fig. 1. The facility (Figs. 2–4) used for simulating the conditions of the environment in space up to 60 thousand kilometers is characterized by the following parameters. The chamber volume is 1, 2 m^3 and maintained at a vacuum level 10^{-5} torr. A xenon lamp (1 kW power) provides a solarlike spectrum, and a particle accelerator provided an electron beam of flux $1, 6 \cdot 10^{10}$ $e - /cm^2/s$ at a beam energy of 8 MeV. The sample can be cryogenically cooled to 120 K. The sample holder in the chamber can be driven by step motor with accuracy of 0, 1 mm providing uniform radiation of area 60×400 mm^2. The created vacuum simulating chamber (VSC) allows to choose one of these conditions and to study in-situ the sample properties under separate or simultaneous influences of these factors. These conditions permit an accelerated testing of materials and products intended for space applications in addition to the design and development of particular applications.

The electron radiation parameters were chosen, which are interesting from the point of view of their application in near-Earth space environment. Moreover, electron radiation is the most convenient and correct means for study of radiation defects regarding simple and complex defects formation.

The radiation fluence was defined by $D = 6,\ 25 \cdot 10^{12}$ It/ $S\,e - /cm^2$, where I is mean current of the beam in μA, t is the exposure time in seconds, and S is the cross section of the beam in cm^2.

Experimental Results and Discussion

In situ measurements of the electroconductivity of silicon single crystals (n-Si) with specific resistance of $\rho = 20$ Ohm · cm ($\sigma = 0,$ 05 $[\mathrm{Ohm} \cdot \mathrm{cm}]^{-1}$) were performed in the VSC. The experimental conditions used in these experiments were as follows: $P = 2\times$ 10^{-5} Torr, $T = 177$ K, $E = 8$ MeV of flux $1, 6 \cdot 10^{10}$ $e - /cm^2/s$, which is by factor 50 higher than in near-Earth space satellite orbits [1,2]. Solar UV radiation originated from a xenon lamp source at an

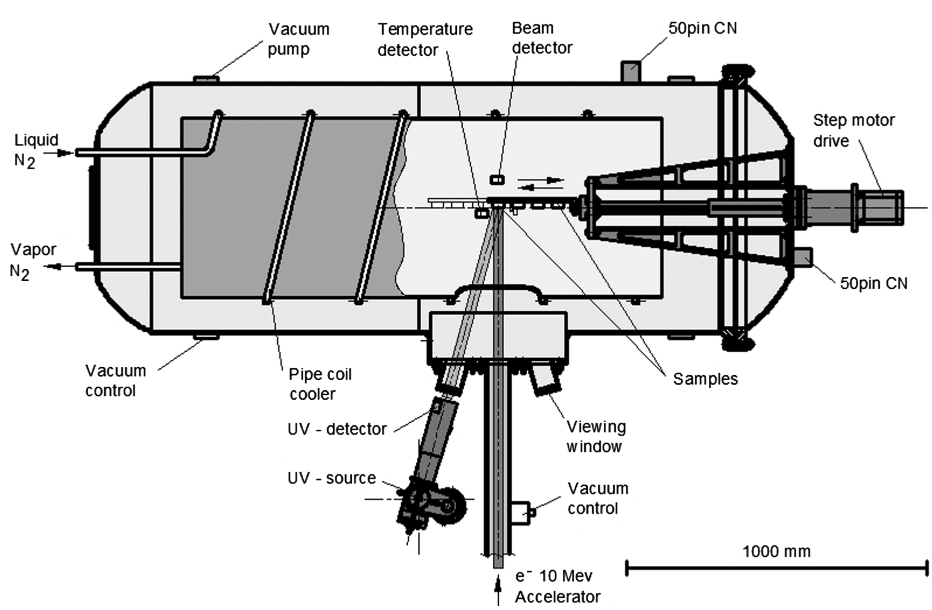

Fig. 3 Horizontal section through VSC.

intensity of 2ES (AMO) suns, which correspond to near-Earth space conditions. The factors varied during experiments were temperature and electron radiation fluence. The experiments were performed with and without UV radiation. The so-called dark conductivity, i.e., conductivity of samples without influence of any factors, was taken as an initial value. After dark value measurements, the UV source was switched on, electron beam was conducted, and σ was measured depending on electron beam fluence.

Decrease of σ almost by factor of 5 (which is the minimal value) is observed after electron radiation with fluence of $5, 76 \cdot 10^{12}$ e − / cm^2 in the presence of UV radiation and then the curve of $\sigma(D)$ has an oscillation behavior (labeled s-1 in Fig. 1).

It can be seen from Fig. 1 (s-3) that the dark value decreases by more than 40% after switching on UV. It increases again with D and reaches equilibrium value which, however, is about 30% lower than the dark value. To clarify the role of experimental conditions on the change of σ in n-Si, the mentioned experiments were also carried out at room temperatures which shows only a weak $\sigma(D)$ dependence, Fig. 1 (s-2).

The observed behavior of σ is explained by the fact that the UV excitation stimulates and the temperature heating suppresses formation of silicon lattice structural radiation defects (RD) in n-Si while in p-Si, it has a different behavior ([3,7]). The σ dependence on electron radiation fluence is nonmonotonous, which can be attributed to charge state variation of RD under UV excitation [3,7]. This effect leads to the localization of conduction electrons around the RD and hence, to the decrease of carriers mobility, i.e., to decrease of σ. During this process new RD are formed and their redistribution takes place. As a result of these interactions, RD complexes are initiated which are stable at room temperatures and define the behavior of σ in silicon sample. Three peaks are observed in Fig. 1 which correspond to the results of [3,7] when at low fluence ion radiation under UV excitation there are three energetic levels responsible for three types of RD. During low fluence electron radiation [8] an oscillation behavior of σ in n-Si was observed which is attributed to RD, containing intrinsic and impurity or primary structural point defects.

The comparison of these results suggests that during the electron radiation process the RD formation character depends on the temperature and UV excitation. At the relatively high radiation fluences of electrons, the low increase of σ indicates that intrinsic structural defects are responsible for RD behavior. Indeed, the experiments of [4,5] performed with electron microscope, show that RD consist of interstitials and vacancies which are clustered at the plane {113}. In general, the introduction of radiation defects leads to reduction of main carrier concentration and their mobility in crystal. The degree of variation of these parameters depends on the initial properties of the Si-samples, radiation energy, fluence, and flux.

Regarding the radiation energy, it should be noted that at high electron energy, when RD clusters are formed, the corresponding centers are more efficient, and changes of parameters occur at lower fluence. Energetic levels of RD in the forbidden gap of n-Si have been determined according to thermal dependency of carrier concentrations at different radiation fluences, taking into account the capture probability of vacancies by matrix and nonmatrix atoms. Apart from known A− centers, (oxygen atom + vacancy) and E− centers (donor atom + vacancy), new centers with Ec − 0, 33 eV; Ec − 0, 40 eV, and Ec − 0, 22 eV have been found and studied. The first one is believed to be connected with interstitial Si atom, the second center appears to correspond to a bivacancy and the third center was identified as bi-vacancy + oxygen (C-center). The appearance of last center can be explained recognizing that during radiation process more vacancies are formed in samples with high resistance (more than 100 Ohm.cm). Part of these vacancies can either connect with each other and be captured with oxygen atom, or form A-center and then connect to other vacancy and form a complex C-center. The main reason for high concentration of vacancies is the high content of carbon atoms that substitute the Si-atom and may promote quasi-chemical RD generation reactions.

At low fluences of radiations, initial defect structure of crystals, their type and concentration of impurity are important [4]. At high radiation range, with the radiation fluence increase the σ tends to some constant value because the impurities are compensated by radiation induced deep levels at Si forbidden gap. In this case the role of intrinsic defects increases in Si. In the meantime, the primary RD concentration increases. At high temperatures, however, it decreases. Therefore, the observed electron radiation induced change of σ at room temperature is lower both with (Fig. 1, s-1) and without UV excitation (Fig. 1, s-2). However, the UV excitation strongly stimulates the process of secondary defect formation at low temperatures. Hence, at electron radiation of n-Si the role of UV excitation is important. In space, the temperature is low enough and it is very important to take into account the influence of UV radiation on the properties of Si-based devices.

It is important to note that radiation defects generated in samples act both as scattering and capture centers, i.e., the mobility and the concentration of carriers decreases. It is shown that the concentration

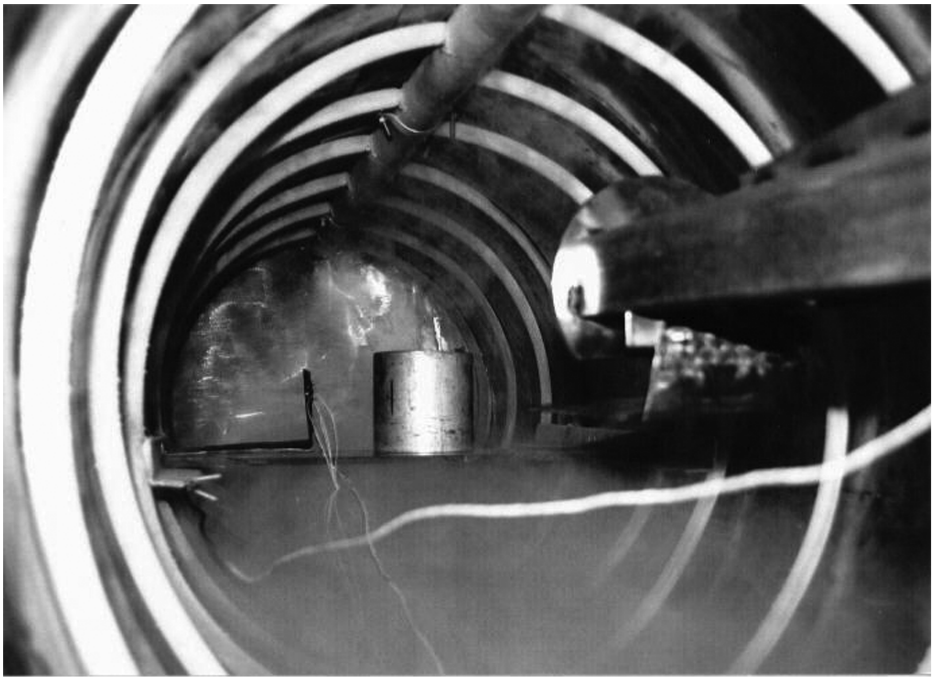

Fig. 4 Inner cross section of the space simulating chamber.

of carriers decreases faster (10^3 times) than the mobility (tenths of percents), so one can assume that the capture properties of radiation defects which takes place under radiation are more important than at postradiation processes.

Note that the σ of Si-samples preliminary radiated at low temperature (under UV excitation) restore their initial value after 3 month storage. This suggests that the formed RD anneals during storage at room temperatures, i.e., they are unstable at low temperatures. This effect is called *aging*, which was observed by many authors. For example in [6] at radiation by O_{6+} (100 MeV) ions in n-Si, the conductivity decreasing for silicon single crystals is described with further recovering of these parameters depending on storage time. Mentioned changes are more expressed at initial storage time: they decrease over time and at a certain storage time these changes tend to zero. For the described case this time is 10 months. An interesting feature was observed in conductivity aging of silicon samples, at its whole recovery the carrier mobility increased by 15% and the concentration decreased also by 15%. As a result, the conductivity reverted to its initial value.

Conclusions

Thus, the investigations of radiation influence on materials show that the results depend on both radiation and further storage conditions. The physical behavior of materials depends on radiation type, flux, and fluence, as well as on environmental conditions (temperature, vacuum). It was shown that with radiation fluence increase, the sample parameters have oscillation behavior around their initial values which indicates that there are multistage processes of radiation defect formation. This is explained by the behavior of radiation defects formed in extreme conditions of space environment.

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D. Edwards
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