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Improvement of radiation stability of semi-insulating gallium arsenide crystals by deposition of diamond-like carbon films

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ABSTRACT

We studied the properties of optical elements for the IR spectral range based on semi-insulating gallium arsenide (SI-GaAs) and antireflecting diamond-like carbon films (DLCF). Particular attention has been paid to the effect of penetrating γ-radiation on transmission of the developed optical elements. A Co^{60} source and step-by-step gaining of γ-irradiation dose were used for treatment of both an initial SI-GaAs crystal and DLCF/SI-GaAs structures. It was shown that DLCF deposition essentially increases degradation resistance of the SI-GaAs-based optical elements to γ-radiation. Particularly, the transmittance of the DLCF/SI-GaAs structure after γ-irradiation with a dose $9 \cdot 10^4$ Gy even exceeds that of initial structures. The possible mechanism that explains the effect of γ-radiation on the SI-GaAs crystals and the DLCF/SI-GaAs structures at different irradiation doses was proposed. The effect of small doses is responsible for non-monotonic transmission changes in both SI-GaAs crystals and DLCF/SI-GaAs structures. At further increasing the γ-irradiation dose, the variation of properties of both DLCF and SI-GaAs crystal influences on the transmission of DLCF/SI-GaAs system. At high γ-irradiation dose $1.4 \cdot 10^5$ Gy, passivation of radiation defects in the SI-GaAs bulk by hydrogen diffused from DLCF leads to increasing the degradation resistance of the SI-GaAs crystals coated with DLCF as compared with the crystals without DLCF.

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1. Introduction

Semi-insulating gallium arsenide (SI-GaAs) has been widely used in various areas of science and technology for many years. For instance, SI-GaAs substrates were applied in manufacturing the integrated circuits and microwave devices [1,2]. Owing to its optical properties, SI-GaAs material has also used in manufacturing technology for optical elements of IR optics [3,4]. For several decades, SI-GaAs was considered to be a promising material for development of radiation spectrometers [5,6], including γ-radiation detectors [5].

The main advantage of SI-GaAs over silicon (another promising material for radiation detectors) is much higher absorption efficiency of γ- and X-rays [6]. At the same time, the main drawback of SI-GaAs is number of growth defects (particularly, EL2 ones form deep levels in the bandgap of the material). Being traps for charge carriers, such defects considerably impair SI-GaAs-based device performance [5].

A necessity of sufficient improvement of quality of SI-GaAs crystals grown by the liquid encapsulated Czochralski method (LEC) has been noted more than two decades ago. It has the great importance for manufacturing radiation detectors as well as for all other SI-GaAs applications. It is also true for production of elements for IR optics because the impairment of the crystalline structure inevitably results in degradation of its optical properties. Recently, due to development of technologies for deposition of high-quality and high-purity GaAs epitaxial layers, the efficient radiation- and photodetectors based on pin-structures with sufficiently thick undoped i-layers have been made [6,7].

Besides high quality of initial SI-GaAs crystals, another important requirement for efficient operation of SI-GaAs-based devices is their resistance to various degradation factors. In case of radiation detectors, such factor is corpuscular, γ- or X-ray radiation itself resulting in generation of additional structural defects during device operation [5,6]. For other devices, such factors become essential during operating under extreme conditions, e.g. action of

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penetrating radiation or accelerated charged particles. Such conditions exist in outer space or can appear on the Earth – say, as the result of extraordinary events.

Among degradation factors, the efficient protection against the penetrating radiation is complicated or even impossible (for optical devices and elements). Evidently, application of protective cases for such devices and elements is excluded. As a result, their parameters become impaired under action of penetrating radiation, and the term of efficient operation decreases.

The reason for impairment of GaAs-based device parameters is generation of radiation defects under irradiation. For example, γ-irradiation produces radiation defects like generation-recombination centres due to the Compton Effect. In this case, shallow defects are partially annealed at a long-term thermal treatment with remaining the deep defects [7]. It was shown [7] that parameters of pin-photodetectors are considerably impaired after γ-irradiation. The dark current grew by three orders of magnitude, while the detector photoresponse decreased by 50% after γ-irradiation with a dose $3.6 \cdot 10^3$ Gy [7].

Another rather important factor of impairment of SI-GaAs properties under penetrating radiation is radiation-induced degradation of material surface or near-surface layer [8,9]. It was shown [8] that destruction of surface of GaAs epitaxial layers starts after the γ-irradiation dose $3 \cdot 10^5$ Gy; the depth of the damaged layer was up to 10 nm at the dose 10^6 Gy. This effect has been studied in details in a wider range (10^2–10^7 Gy) of γ-irradiation doses [9]. The authors [9] shown that the channels of accelerated diffusion of defects into bulk were formed together with radiation degradation of surface.

So, it is necessary to apply protective coatings to prevent the effects mentioned above. It is evident that such coatings for SI-GaAs-based elements of IR optics should also reduce light reflection losses (i.e., these coatings have to be antireflective). They must have the corresponding optical properties and can be either single- [4,10] or multi-layered [3,11]. Earlier it has been shown that diamond-like carbon films (DLCF) can be applied not only as antireflective coatings for SI-GaAs crystals [3,4,10,11] but also to increase the resistance of Si-based solar cells to γ-irradiation [12,13]. Since degradation resistance of DLCF–SI-GaAs structures to γ-irradiation has not been studied yet, the purpose of the present study is such investigations.

2. Experimental

The Cr-doped SI-GaAs (100) crystals with resistivity 10^7 Ohm•cm were grown by the LEC method. The deposition of DLCF with nitrogen content onto SI-GaAs crystals was made by the plasma-enhanced chemical vapour deposition (PE-CVD) at room temperature of the substrate. For this purpose, the bottom electrode of capacitive reactor was cooled with water. The treatment in a hydrogen plasma or argon plasma was processed before DLCF deposition for 15 min at the high-frequency (13.56 MHz) discharge power 175 W in order to clean the sample surface, ensure partial stress relaxation in the crystal and increase the resistance to the following treatments [10,14]. A mixture of methane, hydrogen and nitrogen was used as the precursor gas for the DLCF deposition with the total pressure 100 Pa and the partial pressure of nitrogen 45%. The deposition time was 47 min and the high-frequency (13.56 MHz) discharge power 200 W.

A Co^{60} source of the γ-quanta with the energy 1.25 MeV was used for step-by-step gaining of γ-irradiation doses 10^4 Gy, $5 \cdot 10^5$ Gy, $9 \cdot 10^5$ Gy and $1.4 \cdot 10^5$ Gy for the treatment of the initial GaAs and DLCF–GaAs structures. The dose rate was 0.25 Gy/s and the irradiation was performed in air. The temperature of the samples during irradiation did not exceed 27 °C. Two series of samples were studied. The samples of the first (second) series were treated in the hydrogen (argon) plasma before DLCF deposition.

The IR transmission spectra of the treated samples were measured after each irradiation stage. The DLCF refractive index was measured by the laser ellipsometer LEF-3M at a wavelength λ = 632.8 nm. The IR transmission spectra were measured with a FTIR spectrometer Infralum FT-801 in the spectral range 4–10 μm. Surface morphology of the samples was studied before and after treatments by the atomic force microscope (AFM) Nanoscope IV (Digital Instruments). The Raman spectra were recorded with an automated setup (based on the spectrometer DFS-24 with excitation by a solid-state laser (power 10 mW and wavelength 532 nm). In order to prevent sample heating by laser radiation during measurements the cylindrical lens were used. The experimental spectra were fitted with Lorentzian functions and the peak positions and half-widths were determined.

3. Results and discussion

The IR-transmittance spectra of the SI-GaAs and DLCF–GaAs structures before and after γ-irradiation with different doses are presented on the Figs. 1–3. The SI-GaAs sample with the maximum transmittance *T* in the studied spectral range (Fig. 1, curve 1) was chosen as the reference one. The integral transmittance for that sample was higher than that one for the initial samples used for DLCF–GaAs structures (Figs. 2 and 3, curves 1). It means that the mentioned sample has higher resistivity to the radiation factors due to its higher structural perfection.

After the first γ-dose 10^4 Gy the transmittance of the initial sample increased over the entire studied spectral range (Fig. 1, curve 2). It can be explained by the effect of low doses [15] or, in other words, radiation-induced "ordering" effect, suggesting a restructuring of the lattice [16,17]. In this case, the annihilation of the defects generated by γ-irradiation with those presented in the initial GaAs crystal occurs. Besides, the stimulated gettering of defects and impurities at surface or interface may also takes place [16,17]. It should be noted that effect of improvement of maximum mobility, the minority carrier lifetime, the carrier concentration, the exciton lifetime, and the PL intensity was observed for GaAs earlier after irradiations including electron one [17]. The effect of low doses was also responsible for increasing the transmittance of the DLCF-GaAs structures (Figs. 2 and 3, curves 3) in comparison with the non-irradiated one (Figs. 2 and 3, curves 2). Some

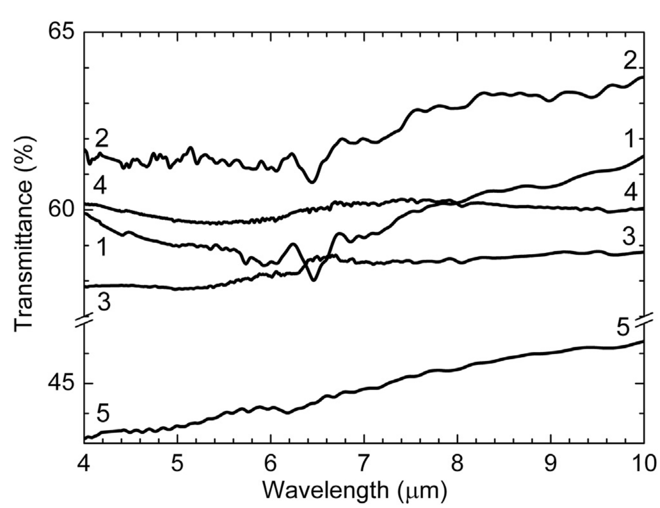

Fig. 1. The IR transmission spectra of GaAs samples: initial (1) and after γ-irradiation with the dose 10^4 Gy (2); $5 \cdot 10^4$ Gy (3); $9 \cdot 10^4$ Gy (4); $1.4 \cdot 10^5$ Gy (5).

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