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Electrical Properties of InP Crystals with Inhomogeneities Regions

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The parameters of potential well, which arises around inhomogeneities of technological origin in n-InP, have been analyzed using electrical measurements data. Model of spherical space-charge regions surrounding disordered regions was applied for explanation of results and found to be in fair agreement with experimental data. Comparison of experimental data with theoretical computations displays scattering of current carriers due to the disordered regions in n-InP additional to lattice and impurity ions scattering.

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1. Introduction

Among the various possible types of inhomogeneities in semiconductors the most frequently occurring ones are disordered areas of technological origin. Independently of crystal growth methods there always exist this or that inhomogeneity, disordered areas. The commonly encountered problem is one when inhomogeneity is large enough to change considerably the semiconductor properties compared with a homogeneous material. It has been concluded [1] that large-sized structure imperfections have an effect on the properties of high-resistant materials, but in low-resistant materials inhomogeneities on the distribution of impurities have a principal influence. Though such crystals are considered as unsuitable material for production of many electronic devices, in some extent these disordered materials are used in special solid-state devices of microelectronics [2–4].

Therefore research of large-scale type defects effect on III–V compounds, particularly on InP electrical properties is of high interest. InP has attracted keen interest in view of its use in electronics, optoelectronics, wireless systems of connection, high-speed microelectronic devices, super high-frequency equipments, quantum devices, high efficiency photovoltaics for Space.

It is important that just at growing of InP crystals we get the greatest number of defects because of extremely high phosphorus vapor pressure reaching several tens of atmospheres and causing great technological difficulties. In addition, the mass of P atoms is twice lighter than the mass of As atoms. So, there is possible the formation of more effective disordered areas in growing process of InP than that of, for example, in InAs. InP crystals containing disordered regions may serve as a suitable material for investigation of the electrical properties of disordered regions. Thus the problem to research InP with disordered areas is very actual and will promote its successful advancement to market. Presently, experimental and theoretical knowledge concerning such materials is quite rudimentary with a few exceptions. This paper is devoted mainly to researching of electrical properties in low-mobility of InP with disordered areas.

2. Experimental

Experimental samples of InP were grown by horizontal zone melting method (sample 1) and the pulling method (sample 2). The data of carriers mobility are obtained from the measurements of the Hall effect and electric conductivity by the compensation circuit at the direct current. Obtained undoped samples of InP were n-type with electrons concentration of 1.5×10^{16} cm^{-3} (sample 1) and 1.2×10^{16} cm^{-3} (sample 2) at 300 K.

Researching samples then were irradiated in the vertical channels of a reactor. Maximum integral flux of fast neutrons was $\Phi = 2\times10^{18}$ n/cm^2. Irradiation of the crystals with electrons of 50 MeV have been carried out on the accelerator with electron flux of $\Phi = 5\times10^{17}$ e/cm^2.

3. Results and discussion

3.1. Current carriers concentration

Investigations before irradiation of the Hall coefficient in the temperature range of 77–300 K in experimental crystals of undoped n-InP samples have shown the weak increase of the carriers concentration with temperature increase, approaching to the impurities exhaustion at 300 K (Fig. 1a).

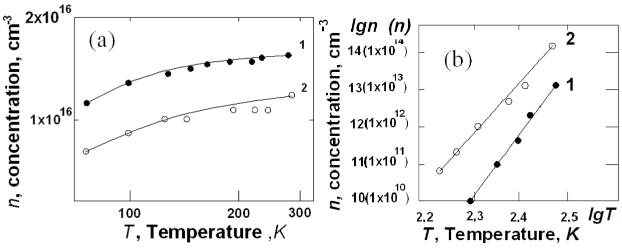

Fig. 1. Temperature variation of electrons concentration (n) in InP crystals before irradiation for sample 1 with $n_0 = 1.5 \times 10^{16}$ cm^{-3} at 300 K (curve 1) and sample 2 with $n_0 = 1.2 \times 10^{16}$ cm^{-3} at 300 K (curve 2) (a) and after irradiation for sample 1 with neutron fluence of $\Phi = 2 \times 10^{18}$ n/cm^2 (curve 1) and for sample 2 with 50 MeV electrons and fluence of $\Phi = 5 \times 10^{17}$ e/cm^2 (b).

The results of electrons concentration in InP crystals after irradiation for two samples are shown in Fig. 1b. Investigations after irradiation have shown that if before irradiation the carriers concentration was changing weakly in the temperature range, after irradiation the carriers concentration, independently of irradiation type, increases strongly with temperature increase (Fig. 1b). The observed phenomenon of sharp decrease of the carriers concentration might be closely connected with the decay by irradiation of large disordered areas, introduced in the material during the process of its growing. Irradiation apparently originates a great number of point-type centres acting as traps for carriers and thereby decreasing the carriers concentration.

3.2. Hall mobility of the current carriers

The results of the measurements before radiation of current carriers mobility (μ) in InP crystals showed extremely low values of mobility (Fig. 2a). In so doing this effect is larger at 300 K than at 77 K. At that temperature dependence of μ differs to that in homogeneous samples. This is the opposite to the scattering on the ions of impurity. It is evident that extremely low values of mobility and its temperature dependence are not the result of point impurity centres action. For explanation of unusual behaviour of mobility in n-InP, it is natural to suppose the presence of the third mechanism of carriers scattering on the disordered areas, arising during the crystal growth, in addition to lattice scattering and the scattering on the impurity ions. These disorder areas give rise of effective scattering of current carriers that leads to the decrease of mobility. It is natural to consider that at the same time there exist the point defects. Their scattering action is apparently of minor importance.

The presence of inhomogeneities in the samples of n-InP was confirmed by a following irradiation of samples. The current carriers Hall mobility increases after irradiation at the all temperatures and the character of its temperature dependence changes in comparison with one in the unirradiated samples.

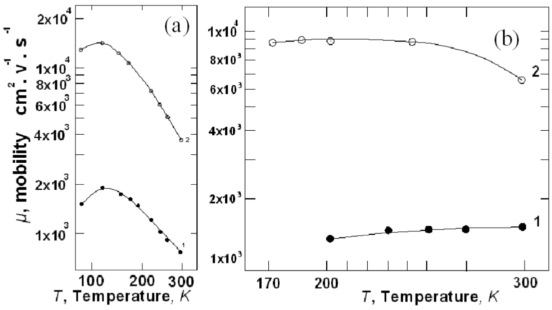

Fig. 2. Temperature variation of Hall mobility (μ) in InP crystals before irradiation for sample 1 with $n_0 = 1.5 \times 10^{16}$ cm^{-3} at 300 K (curve 1) and sample 2 with $n_0 = 1.2 \times 10^{16}$ cm^{-3} at 300 K (curve 2) (a) and after irradiation with neutron fluxes of $\Phi = 2 \times 10^{18}$ n/cm^2 (curve 1) and sample 2 with $n_0 = 2.2 \times 10^{14}$ cm^{-3} at 300 K with 50 MeV electrons and fluxes of $\Phi = 5 \times 10^{17}$ e/cm^2 (curve 2) (b).

After irradiation there was observed the much weaker mobility dependence on the temperature than before irradiation (Fig. 2b). The character mobility change versus temperature for investigating samples irradiated with electrons is the same as after irradiation with fast neutrons as in case of carriers concentration.

Thereby the measurements data of electrical properties and behavior of electrons in InP are in many ways essentially different from the ones in the common perfect semiconductors of the Si, Ge or III–V type and cannot be explained or predicted by the conventional semiconductor theory. Experimental results on temperature-dependent carriers mobility can be well interpreted by using the theoretical model presented in [1, 5] for materials with disordered areas and have been applied to analyze our experimental results. The effect of the disordered regions appears to play a crucial role.

Disordered areas are surrounded with potential wells of sufficient depth and width, therefore they considerably influence on the electrical properties, in particular, they change strongly the Hall mobility. The well generally acts as an isolated nonconductive emptiness. In the first approximation it is assumed that mobility connected with scattering on the disorders is determined by the equation

$$\frac{1}{\mu_{\text{dis}}} = \frac{1}{\mu_{\text{before}}} - \frac{1}{\mu_{\text{after}}}, \qquad (1)$$

where μ_{dis} — mobility connected to the scattering on the disordered areas, μ_{before} — mobility before irradiation, μ_{after} — mobility after irradiation.

The experimental values of μ_{dis} determined from (1) were compared with the mobility, μ_{dis}, defined by the scattering on the space charge regions and calculated according to Weisberg [5] theoretical treatment by equation

$$\mu_{\text{dis}} = e\left[N_{\text{dis}}(2mkT)^{\frac{1}{2}}A\right]^{-1}, \tag{2}$$

where N_{dis} — the concentration of space-charge regions, e — electron charge, m — the effective mass of the current carriers, k — Boltzmann's constant, T — temperature, A — the effective scattering area of the space-charge region. A sphere model of the disordered area is set in the base of this model. A comparison of experimental data with theory provided the possibility of determining parameters of disordered regions in InP crystals. Calculations of μ_{dis} for n-InP samples have given a satisfactory agreement of the theory with the experimental data when the parameters of disordered areas in n-InP samples at 300 K are the following (Table).

TABLE

Parameters of disordered regions in InP at 300 K.

Sample #	Geometric radius of disordered area r_{dis} [cm]	Concentration of disordered areas N_{dis} [cm^{-3}]	Quantity of atoms in disordered area	Effective radius of disordered area r_{eff} [cm]	Depth of electric field penetration W [cm]	Intensity of electric field in barrier E [V/cm]
1	6.2×10^{-7}	4.6×10^{18}	2.0×10^{4}	3.6×10^{-7}	3.5×10^{-5}	7.8×10^{4}
2	2.7×10^{-6}	3.7×10^{16}	1.6×10^{6}	1.8×10^{-6}	4.0×10^{-5}	6.8×10^{4}

The calculations have shown that configuration of electrostatic potential around disordered region creates an isolated area effective radius (radial size of the affected region) which is of the same order as the radius of disordered region and exceeds considerably the lattice parameter of InP. So the presence of large scale disordered areas leads to forming of big space charged areas surrounding inhomogeneities and appearance of potential wells enough depth and width to influence significantly on the bulk electrical properties of crystals.

Thus irradiation with high-power particles causes decay and decrease of the disordered areas volume, which leads to the increase of the carriers mobility after irradiation. It should be noted that irradiation cannot lead to the complete decay and dissolution of the disordered areas. After decay there remain smaller formations which are less effective in the process of scattering.

At the analysis of the carrier mobility resulting from the scattering on the disordered areas we must take into account the effects of leakage and the other complications. More accurate model assumes that not all of the total volume of disordered region is fully insulator. But a treatment of our data shows that to a first approximation the current carriers cannot penetrate into the space charge region considered as isolated regions.

4. Conclusions

The disordered regions in InP affect the local equilibrium carrier densities and act as effective scattering centers with effect on the value of the carrier mobility. It has been shown that in n-InP with the disordered areas irradiation with fast neutrons and high-power electrons leads to the removing of disordered areas and consequently to the increase of the carrier mobility. Obtained results opened the way to extensive efforts to understand and to improve transport properties of semiconductors with disordered regions with a view of technological applications, how to make high-performance devices using semiconductors that are defective, have low carrier mobilities.

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