On the effect of a dopant on the formation of disordered regions in GaAs under irradiation with fast neutrons

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The effect of the irradiation dose and the density and type of dopant on the size of disordered regions in GaAs was studied by x-ray methods. The role of the impurity in the formation of disordered regions and their evolution with dose was analyzed. © *1998 American Institute of Physics.* [S1063-7826(98)01703-7]

The irradiation of semiconductors with heavy particles leads to, together with the generation of point defects (PDs) in the volume of the semiconductor, the formation of disordered regions (DRs).[1] Being a collection of points defects integrated in a local volume, a DR possesses properties which are specific to the semiconductor matrix and are, as a rule, mainly responsible for the degradation of the optical and electrophysical properties of the semiconductor.[2] In this connection it is important to determine the main parameters of DRs experimentally and to study the factors determining these parameters.

In the present work we investigated the effect of the type and level of doping on the effective size of DRs in the case of irradiation of gallium arsenide with fast neutrons. To this end samples of n- and p-type single-crystal GaAs, grown in the [100] direction by the Czochralski method, were selected. The n-GaAs crystals differed by the density N_{Sn} of the main donor impurity $\mathrm{Sn}_{\mathrm{Ga}}$. The density n_0 of equilibrium electrons in these crystals was determined by the dopant density and at $T=300$ K equalled $2\times10^{16}-2\times10^{18}$ cm^{-3}. The p-type crystals were doped with zinc atoms ($\mathrm{Zn}_{\mathrm{Ga}}$) and the hole density in the crystals was $p_0=2\times10^{18}$ cm^{-3} at $T=300$ K. The dislocation density was virtually the same in the experimental n-GaAs(Sn) and p-GaAs(Zn) crystals and equalled $(2-3)\times10^4$ cm^{-2}. The samples were irradiated with fast neutrons (average energy $E_n=2$ MeV) with doses $\Phi_n=10^{15}-10^{17}$ neutrons/cm^2 in a reactor channel with forced cooling (the temperature of the samples did not exceed 60 °C). The density N_S of point defects induced by neutron irradiation with dose Φ_n and the density N^* of disordered regions are proportional to Φ_n and equal $50\cdot\Phi_n$ and $0.21\cdot\Phi_n$, respectively.[3] As is well known, when semiconductors are irradiated with fast electrons with dose Φ_e, TDs are produced (their density equals $5\cdot\Phi_e$), while DRs do not form right up to very high doses.

The irradiated crystals were investigated by x-ray topography and diffractometry methods.[4,5] According to the x-ray topographic data, the dislocation density remained virtually unchanged during irradiation. The static Debye–Waller factor L, which characterizes the relative volume fraction of the distorted lattice in the crystal, was determined by the method of Ref. 5. On the basis of the fact that the dislocation density in the crystals remained unchanged during irradiation, all changes (ΔL) in the value of the static factor can be attributed to the formation of DRs. The correction ΔL is related with the density N^* of DRs and the average effective size R_{av} for the cluster model by the formula[6]

$$\Delta L=N^*\cdot R_{av}^5. \tag{1}$$

Thus, using the dose dependence of N^*, the value of R_{av} and its evolution as a function of the irradiation dose can be easily calculated from the experimental values of ΔL. The dose dependences of R_{av} calculated from Eq. (1) for irradiated n- and p-type crystals are presented in Fig. 1. The change in the ratio of the components in the crystals during irradiation was monitored by measuring the total intensities for quasiforbidden reflections.[7] These results are presented in Fig. 2.

To analyze the dependences obtained we shall proceed from the model for DRs which has become firmly established in the last few years.[2] Four basic stages are distinguished in the process leading to the formation of DRs: cascade, postcascade, quasichemical, and accomodation. During the first two stages a 50–150 Å nucleus of a DR forms over very short times ($10^{-14}-10^{-13}$ and $10^{-11}-10^{-10}$ s, respectively). During the quasichemical stage PDs (mainly interstitial atoms As_i and Ga_i) displaced from the cascade actively diffuse toward sinks in the semiconductor matrix, where they either recombine or form complicated defects or defect–impurity complexes (DICs). The sinks can be both growth defects and PDs induced in the matrix. These so-called accomodation processes occur during the entire accumulation time of the irradiation dose.

Thus, the size of a DR will be determined by the size of the defect-impurity shell (DIS), consisting of cluster of different types of DICs, that forms around the nucleus of the DR. From the standpoint of x-ray measurements, a DIS is a distorted region of the crystal lattice of GaAs near the nucleus of the DR. The effective size of this distorted region is proportional to the deformation gradient produced by the distribution of DICs between the DR nucleus and the unperturbed matrix. As the DR density increases (overlap process), the deformation level of the entire crystal increases and the detected limit of the deformation gradient shifts closer to the DR nucleus (the effective size R_{av} decreases).

As one can see from the curves presented in Fig. 1, the effect of the doping level on the value of R_{av} is substantial at low irradiation doses ($\Phi_n=10^{15}$ neutrons/cm^2). As the dose increases, the dependence of R_{av} on the density of the dopant atoms decreases and completely vanishes when $\Phi_n>10^{16}$

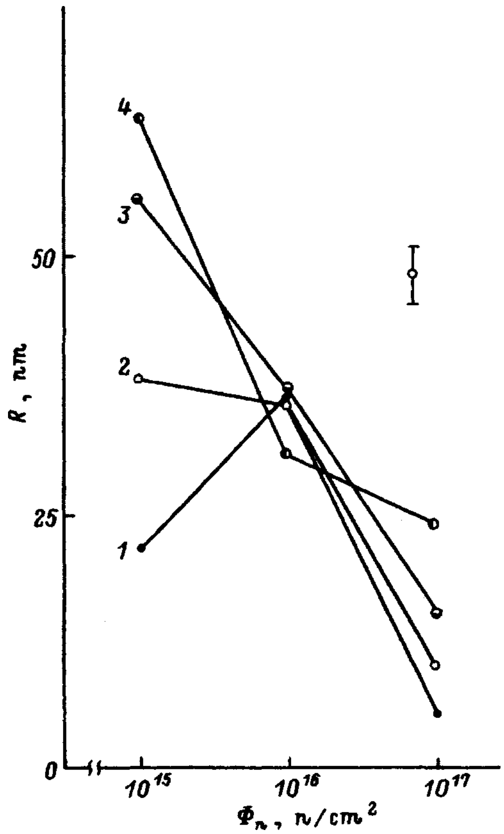

FIG. 1. Effective sizes R of disordered regions in GaAs versus the neutron irradiation dose and doping level. *1, 2, 3* — Crystals doped with Sn to density 2×10^{16}, 2×10^{17}, 2×10^{18} cm^{-3}, respectively; *4* — Zn with $N_{Zn}=2\times10^{18}$ cm^{-3}.

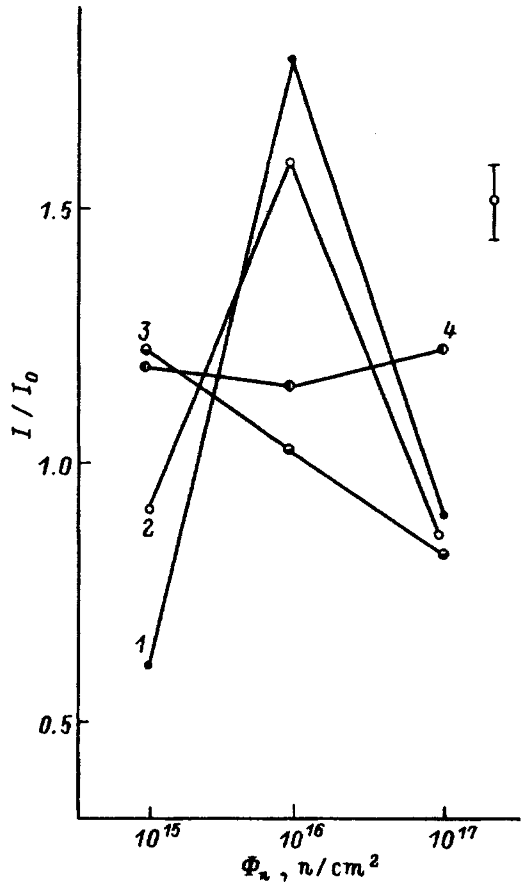

FIG. 2. Ratio I/I_0 of the total intensities of quasiforbidden x-ray reflections (200) measured in the irradiated (I) and initial (I_0) crystals versus the irradiation dose and doping level. The designations are the same as in Fig. 1.

neutrons/cm^2. The character of the variation of R_{av} with irradiation dose in samples with different doping levels shows that R_{av} is determined by several basic factors. In the case of low doses the generation of PDs in the GaAs matrix has virtually no effect on the properties of the matrix and, specifically, $N_S<N_{Sn}$ for all values of N_{Sn}. Moreover, since the DR density is low, the average distance between separate DRs is greater than R_{av}, i.e., the DRs are isolated (their DISs do not overlap). These considerations and the data presented above suggest that for low irradiation doses a) DRs form mainly at the quasichemical stage (accomodation processes have virtually no effect on the formation of DRs) and b) the increase in R_{av} with increasing doping level is due to the PDs displaced from the cascade interacting effectively with the Sn_{Ga} atoms accompanied by the formation of DICs. Analysis of Fig. 2 shows that the number of As_i and Sn in DRs increases. As the irradiation dose increases, on the one hand N^* increases and at a definite value of Φ_n the DRs can no longer be regarded as being isolated (i.e., their DISs start to overlap), as a result of which R_{av} should decrease. On the other hand, as Φ_n increases so does N_S, for a given value of N_{Sn} $N_S>N_{Sn}$, and R_{av} can increase as a result of decoration by PDs generated in the matrix. As one can see from the dose dependences of R_{av}, at the maximum value of N_{Sn}, for which R_{av} of an isolated DR is maximum, increasing Φ_n results in overlapping of the DRs and a decrease in the value of R_{av}. At the minimum level of doping and, correspondingly, the minimum value of R_{av} of an isolated DR, increasing the dose load increases R_{av} as a result of accomodation processes as long as the DRs are isolated. For $\Phi_n>10^{16}$ neutrons/cm^2 the overlapping of the DISs is the dominating factor and for all samples, irrespective of the value of N_{Sn}, the effective size of the DRs decreases.

It is important to note that the character of the change in R_{av} with irradiation dose Φ_n is virtually the same in GaAs samples with different types of conduction but the same dopant density ($N_{Sn}=N_{Zn}$) (Fig. 1). This also attests to the fact that the dopant atoms are effective sinks for PDs during the formation of DRs.

In summary, the radiation defects produced by irradiation with fast neutrons are not purely vacancy defects. Most likely, in our case complexes of vacancies and interstitial atoms as well as complexes of of primary defects with technological impurities (dopants) are formed in the regions of disordering. The largest changes in the system of point defects occur at a dose of 10^{16} cm^{-2} (Fig. 2), In addition, these changes are all the larger, the lower the doping level of the crystals. An increase in the size of the DRs is also observed up to irradiation doses of 10^{16} cm^{-2}. Further limitation on size is due to the overlapping of the deformation fields of different DISs.

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