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Abstract

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PHYSICS

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ON THE INFLUENCE OF ALLOYING IMPURITIES ON THE ANISOTROPY OF PLASTIC DEFORMATION OF GaAs SINGLE CRYSTALS

(Presented by Academician N. P. Sazhin, 6 VI 1968)

One of the most widespread types of dislocations in crystals with a diamond- or zinc-blende-type structure is the 60° dislocation ([1,2]). In the latter case, owing to the absence of an inversion center in the lattice, there must be a difference in atomic structure and properties between dislocations of different sign, as Haasen first pointed out ([2]). In this connection, in semiconductor compounds A_3B_5 two types of 60° dislocations (α and β) are distinguished, depending on which kind of atoms terminates the extraplane of the dislocation. It should be noted that, despite the existence in the literature of various models of the atomic structure of 60° α- and β-dislocations ([3–5]), the question of the configuration of the bonds in the core of these dislocations remains open. In real A_3B_5 crystals, dislocations of both types are present in approximately equal amounts, which makes it difficult to differentiate their influence on the properties of the single crystal. For an experimental study of the properties of a definite type of dislocation, plastically deformed or specially grown single crystals were usually used, in which α- or β-dislocations predominated. Mainly InSb single crystals were investigated. It has been established that α- and β-dislocations affect the electrical properties of crystals differently and also interact differently with etchants ([3,6–11]).

Table 1

Properties of the investigated GaAs single crystals

No.	Conductivity type	Alloying impurity	Conc. of alloying impurity, cm^{-3}	Carrier conc., cm^{-3}	Dislocation density, cm^{-2}
1	n	–	–	$1.6 \cdot 10^{16}$	$9 \cdot 10^{3}$
3	p	Zn	$7 \cdot 10^{18}$	$7.0 \cdot 10^{18}$	$8 \cdot 10^{3}$
2	p	Zn	$2.5 \cdot 10^{19}$	$2.5 \cdot 10^{19}$	$1 \cdot 10^{4}$

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No.	Conductivity type	Alloying impurity	Conc. of alloying impurity, cm^{-3}	Carrier conc., cm^{-3}	Dislocation density, cm^{-2}
4	n	Te	$5 \cdot 10^{18}$	$4.0 \cdot 10^{18}$	$6 \cdot 10^{3}$

In work ([12]) it was shown that, with an appropriate choice of the orientation of InSb crystals, a noticeable difference is observed in creep characteristics depending on the direction of bending of the specimens, i.e., there is a pronounced anisotropy of plastic deformation of the single crystals studied. The results obtained are associated with a difference in the mobility of α- and β-dislocations in InSb introduced during bending. In view of the noted difference in the structure and properties of α- and β-dislocations in A_3B_5 crystals, it is natural to expect that these dislocations interact differently with impurity atoms. One of the effective methods for studying such interaction is the investigation of the influence of alloying impurities on plastic deformation. In this connection, the purpose of the present work was to investigate the anisotropy of plastic deformation in GaAs single crystals with different contents of donor and acceptor impurities.

The work was carried out on GaAs single crystals grown by the Czochralski method, the principal properties of which are given in Table 1.

The plastic deformation of the specimens was carried out by the method of three-point bending on a special apparatus that made it possible to study creep in an inert-gas atmosphere over a wide range of stresses and temperatures. The orientation of the specimens was chosen so as to make it possible, depending on the direction of bending, to introduce into the crystal predominantly either α- or β-dislocations ([10,13]). Creep was studied in the temperature interval 400-700°. In this case the stress was kept constant at 6 kG/mm^2. A study of specimens of undoped GaAs revealed a substantial anisotropy of plastic deformation. The parameters of the creep curves differed markedly for identical specimens depending on which dislocations predominated in the crystal for the chosen direction of bending. Let us denote conventionally by the symbol α the bending direction that leads to generation of "Ga-dislocations," and by the symbol β the direction in which "As-dislocations" are generated. Over the entire investigated temperature interval, specimens deformed in the α direction proved to be more plastic than in the β direction. For example, at 450° and $\tau = 6$ kG/mm^2, specimens with α orientation had the following creep parameters: initial period $t_i = 80$ sec, steady-state creep rate $\dot{\varepsilon}_w = 7.6 \cdot 10^{-2}\%$ sec^{-1}. Under the same conditions, for specimens with β orientation, $t_i = 200$ sec, $\dot{\varepsilon}_w = 2.4 \cdot 10^{-2}\%$ sec^{-1}. This means that the mobility of α-dislocations in GaAs is higher than that of β-dislocations.

Fig. 1. Temperature dependence of the incubation period of creep of GaAs. 1 –No. 4 (Table 1), β; 2 –No. 4, α; 3 –No. 1, β; 4 –No. 2, α; 5 –No. 3, β; 6 –

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Fig. 1. Temperature dependence of the incubation period of creep of GaAs. 1 —No. 4 (Table 1), β; 2 —No. 4, α; 3 —No. 1, β; 4 —No. 2, α; 5 —No. 3, β; 6 —No. 3, α; 7 —No. 2, β; 8 —No. 1, α.

Figure 1: Fig. 1. Temperature dependence of the incubation period of creep of GaAs. 1 —No. 4 (Table 1), β; 2 —No. 4, α; 3 —No. 1, β; 4 —No. 2, α; 5 —No. 3, β; 6 —No. 3, α; 7 —No. 2, β; 8 —No. 1, α.

Fig. 2. Temperature dependence of the steady-state creep rate of GaAs. The designations are the same as in Fig. 1

Figure 2: Fig. 2. Temperature dependence of the steady-state creep rate of GaAs. The designations are the same as in Fig. 1

No. 3, α; 7 —No. 2, β; 8 —No. 1, α.

The results obtained are presented graphically in Figs. 1 and 2, from which an exponential dependence of t_i and $\dot{\varepsilon}_w$ on temperature follows. The values of the activation energy of creep found from the slopes of the straight lines are given in

Table 2

Values of the activation energy for dislocation motion, obtained from creep experiments on GaAs

From which dependence obtained	GaAs pure α	GaAs pure β	GaAs + Zn (10^{18}) α	GaAs + Zn (10^{18}) β	GaAs + Zn (10^{19}) α	GaAs + Zn (10^{19}) β	GaAs + Te (10^{18}) α	GaAs + Te (10^{18}) β
$\ln t_i = f(1/T)$	1.25 ± 0.05	1.60 ± 0.05	1.26 ± 0.05	1.33 ± 0.05	1.51 ± 0.05	1.51 ± 0.05	2.20 ± 0.05	2.40 ± 0.05
$\ln \dot{\varepsilon}_w = F(1/T)$	1.20 ± 0.05	1.70 ± 0.05	1.26 ± 0.05	1.35 ± 0.05	1.40 ± 0.05	1.45 ± 0.05	2.20 ± 0.05	2.40 ± 0.0

Table 2. According to the creep theory of nearly perfect crystals ([14]), the values obtained characterize the activation energy for dislocation motion in the crystal. Consequently, it may be concluded that the activation energy of β-dislocations in GaAs exceeds the corresponding value for α-dislocations, which may explain the above-noted difference in the plasticity of the crystals for different bending directions.

Fig. 2. Temperature dependence of the steady-state creep rate of GaAs. The designations are the same as in Fig. 1.

Doping has a substantial effect on the plasticity of GaAs crystals for both bending directions. As follows from Fig. 2, the introduction into GaAs of $\sim 10^{18}$ atoms/cm^3 Zn leads to a considerable increase in the plasticity associated with β-dislocations and at the same time only very slightly lowers the plasticity associated with α-dislocations. Thus, a different character of the interaction of Zn atoms with α- and β-dislocations in GaAs is observed. As a result, in crystals with a Zn concentration of $7 \cdot 10^{18}$, the anisotropy of plastic deformation

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is manifested very weakly. The values of the activation energy change accordingly (Table 2). A further increase in the Zn concentration to 10^{19} cm^{-3} is accompanied by some decrease in plasticity for both bending directions, while the dependence on the direction of deformation still remains practically absent.

Doping gallium arsenide with the donor impurity Te leads to a sharp strengthening of the crystals. In this case the creep anisotropy is retained, although it is less pronounced than in the undoped material. A substantial increase is observed in the activation energy for the motion of α- and β-dislocations.

The noted influence of doping on the anisotropy of plastic deformation in GaAs is apparently due to the effect of the alloying impurities on the mobility of α- and β-dislocations. Motion of dislocations in the lattice of A_3B_5 is accompanied by the rupture of directional covalent bonds, as a result of which such displacement requires overcoming high energy barriers (Peierls barriers). Under these conditions the resistance to dislocation motion will depend substantially on the configuration of bonds in the core, in particular on the presence and degree of filling of unsaturated bonds along the dislocation line. According to existing ideas ([3–5]), β-dislocations contain a larger number of electrons per broken bond than α-dislocations. This may be the reason for the energetically more difficult displacement of β-dislocations in A_3B_5 crystals. It should be noted that in InSb β-dislocations are also less mobile ([12]).

In this connection it may be supposed that acceptor Zn ions bring-

lead to a decrease in the number of unpaired electrons along the β-dislocations, bringing their structure closer to that of α-dislocations. A stronger interaction of Zn with β-dislocations, due, in addition to elastic interaction, to electronic interaction, was also indicated in (13, 15). As a result, at a Zn concentration of $\sim 7 \cdot 10^{18}$ cm^{-3}, the difference in the electronic structure of the bonds and in the mobility of α- and β-dislocations becomes very small. Therefore, a further increase in the Zn concentration reduces to the same extent the mobility of dislocations of both signs, leading to a certain decrease in plasticity.

Doping with tellurium leads to a very strong decrease in the mobility of α- and β-dislocations. However, as follows from the data in Table 2, the effect of Te on the activation energy for motion of α-dislocations is somewhat greater. Thus, doping with both donor and acceptor impurities leads to a weakening of the anisotropy of plastic deformation. We do not dwell on the question of the nature of the influence of Te on the plasticity of GaAs, since this has been considered earlier (16, 17).

A more detailed consideration of the mechanism by which alloying impurities influence the anisotropy of plastic deformation requires a definite model of the structure of α- and β-dislocations and lies beyond the scope of the present work.

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