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Dislocation motion in InSb crystals under a magnetic field

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Abstract
Dislocation displacements under the action of a permanent magnetic field without mechanical loading in differently doped InSb crystals are investigated. The dependences of the mean dislocation path length and the relative number of divergence and tightening half-loops on the magnetic induction and preliminary load are obtained. Experiments on n-InSb crystals with Te impurities and on p-InSb crystals with Ge impurities have shown a sensitivity of the magnetoplasticity to the conductivity type and the dopant content. Study of the magnetoplastic effect in the initial deformed InSb crystals shows that internal stresses decrease the lengths of divergence dislocation paths and simultaneously increase the threshold magnetic field above which the magnetoplastic effect exists. Possible reasons for the observed phenomena are discussed.

1. Introduction

The magnetoplastic effect, manifesting itself as dislocation displacements under the action of a permanent weak magnetic field without mechanical loading, was discovered first in NaCl single crystals [1]. For the last decade this effect has been found and investigated in detail in other alkali halides [1–8] and nonmagnetic metals [9, 10]. Macroscopically, the magnetoplastic effect revealed itself as a lowering of yield points of nonmagnetic crystals under the action of a magnetic field [2], a diminishing of its microhardness [3] and change of the internal friction parameters [4, 5] and creep velocity [17]. Recently, the effect was observed in polymers [11, 12], molecular crystals [13], semiconductors [14–16] and segnetoelectrics [17].

The analysis of the main properties of this effect shows that dislocations move due to the internal stress field of other dislocations, but the external magnetic field created conditions for dislocation depinning from local defects. The whole complex of data exhibits that the magnetic field changes the spin state of a dislocation + paramagnetic impurity system, which leads to the lifting of quantum forbiddenness for electron processes in this system. As a result, local barriers appear to be lower or broken down and dislocations depin from defects. A similar principle of spin selection lies at the origin of phenomena which are connected with the influence of a weak magnetic field on the different physical and chemical processes [18, 19].

This paper deals with the study of the influence of the conductivity type, the dopant concentration and the preliminary loading of samples on the dislocation displacements under a magnetic field in InSb crystals.

2. Experimental details

Experiments were carried out on InSb single crystals of both conductivity types and different dopant concentrations: n-type (1×10^{14}; 1×10^{18} cm^{-3}) and p-type (5×10^{13}; 1.6×10^{14}; 1×10^{17}; 1×10^{18} cm^{-3}).

The samples were cut out in the form of quadrangular bars with the dimensions $3 \times 1.5 \times 40$ mm in the [111], [112] and [110] directions, respectively. To introduce 'fresh' dislocations, a slight scratch in the [110] direction on the (111) surface was made with a corundum needle. During subsequent deformation by four-point bending around the [121] axis at elevated temperatures for some minutes, the 60° fast dislocations ran away at 1000–2000 μm from the scratch [20, 21]. The prepared samples were exposed to a static magnetic field for a time in the range from some seconds to 30 min in the absence of additional mechanical loading. The experiments were performed at elevated temperatures with slow preheating for 50 min and similarly slow cooling. The initial and final positions of the dislocations respectively before and after magnetic treatment were fixed by selective chemical etching (5 parts of HNO_3 + 3 parts of HF + 3 parts of CH_3COOH) [14–21].

3. Experimental results and discussion

The magnetoplastic effect in semiconductor InSb single crystals manifests itself as the primary motion of dislocation half-loops away from the scratch (divergence dislocations) under the action of a magnetic field without mechanical loading at elevated temperature [14]. Simultaneously, dislocation displacements towards the scratch (tightening dislocations) are observed. The controlled annealing of samples in the absence of a magnetic field produces on the whole tightening dislocation motion. Only 4% of the total number of mobile dislocations move away from the scratch during the annealing without a magnetic field. It turned out that the relative number (n/N; N is the total number of mobile dislocations) of tightening dislocations decreased with magnetic induction increase and, correspondingly, the relative number of divergence dislocations increased. After reaching some 'field of inversion', these dependences are saturated (figure 1).

The influences of the conductivity type and the dopant content of InSb single crystals on the magnetoplastic effect were found. The dependences of the mean divergence dislocation path lengths in InSb single crystals of both conductivity types and different dopant contents on the magnitude of the magnetic induction were obtained. Mean tightening dislocation path lengths did not depend on the magnitude of the magnetic induction. Figure 2 shows that doping of pure (n-type, 1×10^{14} cm^{-3}) InSb crystals (curve 1) by Te up to 1×10^{18} cm^{-3} (points 5) leads to disappearance of the magnetoplastic effect, as the divergence dislocation paths in doped crystal are background ones. In addition, the relative number of tightening dislocations in this crystal increases to 80–90%, which is typical of annealing.

However, the magnetoplastic effect is more pronounced in p-type InSb crystal which was doped with Ge—even to the same concentration (1×10^{18} cm^{-3}, points 3 on figure 2) as that of the Te: within the experimental error ($\approx$15%), the divergence dislocation path lengths match the ones in pure InSb crystal. Divergence dislocation paths decrease in length with the diminishing of the Ge impurity concentration (figure 2; point 4 is obtained as an average of five sample data). The magnetoplastic effect disappears with diminishing of the Ge impurity concentration to 1.6×10^{14} cm^{-3}. It should be noted that the dislocation path lengths in the

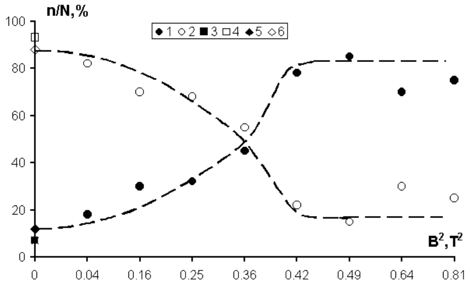

Figure 1. The dependences of the relative numbers n/N of divergence (1, 3, 5) and tightening (2, 4, 6) dislocations on the magnetic induction B for InSb-I (n-type, 1×10^{14} cm^{-3}) crystal; $t = 10$ min, $T = 200\,^{\circ}$C; 3, 4: annealing only; 5, 6: switching on and off of the electromagnet.

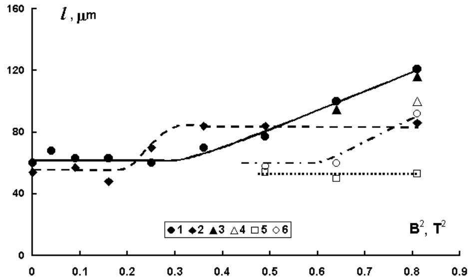

Figure 2. The dependences of the mean path lengths l of divergence dislocations on the magnetic induction B for InSb crystals: n-type: 1, 6: InSb-I (1×10^{14} cm^{-3}), 2: InSb-II (1×10^{14} cm^{-3}), 5: InSb(Te) (1×10^{18} cm^{-3}); and p-type: 3: InSb(Ge) (1×10^{18} cm^{-3}), 4: InSb(Ge) (1×10^{17} cm^{-3}) for preliminary mechanical loadings 15 MPa (1–5) and 10 MPa (6); $T = 200\,^{\circ}$C, $t = 10$ min.

same InSb crystals increased a little with rising Te impurity concentration but decreased very much with rising Ge concentration under mechanical loading in the absence of a magnetic field [20]. So the opposite phenomenon is observed in the same crystals under 'magnetic treatment' without mechanical loading. It is possible that not only the conductivity type but also the magnetic state of the dopant is very important for dislocation motion under a magnetic field. Possibly the Te doping of InSb crystal leads to hardening of the crystal, like what was found for NaCl(Pb) single crystal [8].

A comparison of the dislocation motions under a magnetic field in three n-type InSb crystals of the same carrier concentration—1×10^{14} cm^{-3}—was carried out. Testing of the temperature dependences of the electroconductivity and chemical analyses of the samples from the three crystals did not reveal any difference between them. But the dislocation motions in these crystals under the action of a magnetic field differ very much. Figure 2 shows the dependences of the mean divergence dislocation path lengths in InSb-I [14] (curve 1) and InSb-II (curve 2) on the magnitude of the magnetic induction. Saturation of curve 2 is observed. The level of the saturation in InSb-II depends on neither magnetic treatment time nor the magnitude of the preliminary mechanical load. The saturation level seems to be a result of the existence of some unknown nonmagnetic impurities in InSb-II crystal not surmounted by dislocations under a magnetic field. All transmission bands and (separately) the absorption band edges of both InSb-I and InSb-II crystals were studied. Smaller changes in the spectrum structure and a smaller shear of the absorption band edge in InSb-II crystal compared with those for InSb-I are found. The cause of these changes is still not clear.

Although the fast 60° dislocation motions in the InSb-III and InSb-I crystals under mechanical loading were alike, their displacements under the action of a magnetic field without mechanical loading differ very much. Dislocation half-loops in InSb-III crystal under a magnetic field only tighten. So the magnetoplastic effect is not observed in this crystal. But it manifests itself in InSb-I crystal best of all.

The study of dislocation motion under a magnetic field in three InSb crystals with the same carrier concentration allows us to conclude that the magnitude of the magnetoplastic effect is influenced either by a small content of unknown magnetosensitive impurities or different magnetic states of the same impurity in different crystals, which can promote crystal hardening under a magnetic field like that seen in [8].

The effect of the magnitude of a preliminary mechanical loading, being used to 'distil off' dislocations from a scratch, on their motion under a magnetic field was examined in InSb-I

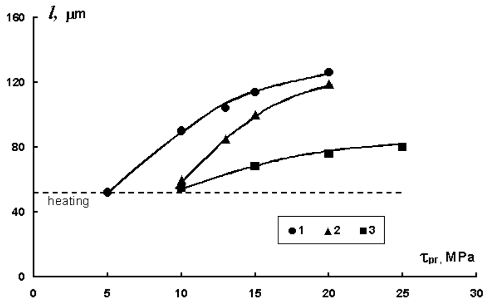

Figure 3. The dependence of the mean path length l for divergence dislocations in InSb-I (n-type, 1×10^{14} cm^{-3}) on the magnitude of the preliminary mechanical load τ_{pr} for different values of the magnetic induction B: 1: 0.9 T, 2: 0.8 T, 3: 0.7 T; $T = 200\,^{\circ}$C, $t = 10$ min.

crystal. The magnitude of this load governs the level of internal stresses in crystals due to the dislocation density in beams extending from a scratch. Figure 3 shows the dependences of the mean divergence dislocation path lengths l for three values of the magnetic induction on the magnitude of a preliminary mechanical load τ. The dislocation displacements under a magnetic field increase but the value of the magnetic induction above which divergence dislocations start to move decreases with increase of the preliminary load (figures 2 and 3). So the level of internal stresses in crystals governs not only the lengths of mean dislocation paths but also the threshold magnetic induction determining the beginning of the magnetoplastic effect. Our data show that the role of the magnetic field reduces to the detachment of dislocations from local defects; then dislocations move under the action of the internal stress field of InSb crystals like in alkali halides [6, 7] and nonmagnetic metals [9, 10].

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