IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

Magnetic field anisotropy of electron-impurity scattering in Al-Y alloys

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

1995 J. Phys.: Condens. Matter 7 6271

(http://iopscience.iop.org/0953-8984/7/31/010)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 171.66.16.151
The article was downloaded on 12/05/2010 at 21:51

Please note that terms and conditions apply.

J Phys.: Condens. Matter 7 (1995) 6271–6278. Printed in the UK

Magnetic field anisotropy of electron–impurity scattering in Al–Y alloys

S E Demyanov, A A Drozd, A V Petrov and M L Petrovskii
Institute of Physics of Solids and Semiconductors, Academy of Sciences of Belarus,
220072 P Brovka Street 17, Minsk, Belarus

Received 5 January 1995, in final form 3 April 1995

Abstract. In the present paper the results of studies of the deviations from Matthiessen's rule (DMRs) in single-crystal Al–Y alloys in magnetic fields up to 8 T are represented. The results obtained bear witness to the anisotropic behaviour of the mechanisms of conduction electron scattering from phonons and impurity atoms. In the analysis of experimental data, a correlation was revealed between the behaviour of the temperature dependences of the DMRs and the direction of the magnetic field relative to the crystallographic orientation of the specimen, and an explanation of the negative value of the DMR observed in the experiment is given.

1. Introduction

Deviations from Matthiessen's rule (DMRs) in charge-transfer processes in metals at low temperatures remains at present one of the most intriguing and contradictory phenomena. In the large number of publications devoted to this problem, beginning in the 1970s and 1980s [1–6], there appeared more than ten theoretical models and a large number of various experimental results, which often contradict each other.

The most detailed studies of the DMR on electron–impurity scattering were carried out on pure metals, alloyed by nonmagnetic impurities with concentrations not exceeding 1 at.%. The temperature and concentration dependences of the impurity part of electrical resistivity $\Delta\rho(T, c)$, which in fact is a measure of the DMR Δ, were used as the objects of these investigations.

All the researchers have a common point of view concerning the linear character of the $\Delta(T)$ dependence at high temperatures in conditions of dominant elastic electron–phonon scattering, but in the low-temperature region, where the DMR has a large value and complicated behaviour, the investigators give various analytical treatments of their results. All the authors recognize that, in general, the problem of the low-temperature behaviour of $\Delta(T)$ deals with the competing processes of electron scattering from phonons and impurity atoms, but they introduce various mechanisms for these types of scattering. In one group of studies, experimental data were satisfactorily explained by the interference of inelastic electron–phonon scattering and elastic electron–impurity scattering processes [1, 2]; in another group of research papers the explanation deals with the anisotropic character of scattering processes on the local regions of Fermi surface [3, 4]; in a third group of investigations, according to the point of view of their authors, it is stated that taking into account the diffusion type of electron motion during the small-angle scattering process is sufficient to explain the results [5, 6].

Most experimental investigations were made on dilute alloys of Al, which traditionally became the model object of research. Generalizing the results of the DMR studies on Al

0953-8984/95/316271+08$19.50 © 1995 IOP Publishing Ltd

alloys (for example [2, 3, 7]), the reasons can be named which in our opinion did not allow us to analyse these results from a united point of view.

(1) In the main, the studies were made on alloys with impurity concentrations in the range 0.05–1 at.% and with low values of residual resistivity ratio (RRR < 100).

(2) The investigations were performed mainly on polycrystalline specimens, containing an uncontrolled quantity of crystal lattice defects.

(3) Practically, such studies have not yet been made in strong magnetic fields, which has a substantial influence on the scale of the anisotropy of the conduction electron distribution function.

In the present work, for the example of Al–Y dilute alloy single crystals, we attempt to show that, when detail studies of structurally perfect specimens in strong and transverse magnetic fields are carried out, the general features of the DMR at low temperatures and correlation between dominant electron scattering processes and the anisotropy of the electron distribution function can be determined.

2. Specimen preparation and experimental methods

During the present research, measurements of the electrical resistance and transverse magnetoresistance of Al single crystals alloyed with Y in the range 10^{-4}–10^{-2} at.% were made. The concentration of alloying addition of Y was lower than its limit of solubility in Al, which equals 0.051 at.% [8]. Al was chosen as the metal matrix because its electron structure and electron scattering mechanisms, which are dominant at low temperatures, have been studied sufficiently well. The choice of an alloying component is caused by the fact that Y is isovalent to Al, and it has a considerably larger atomic radius than Al. Even a small addition of Y must lead to the appearance of a significant value of the impurity resistance and, correspondingly, Δ.

Single crystals of Al–Y alloys, which are dilute solid solutions, were grown in high vacuum by means of the Czochralski method. The single crystals were studied by x-ray radiometric analysis with the use of ^{109}Cd as the radiation source. The analysis of the Y content in Al was made at different angles to the growth axis of crystal. It was found that the nonuniformity of the Y distribution through the volume of Al–Y ingots does not exceed 10%. This result was confirmed by precision measurements of the electrical resistance (up to 10^{-12} V) and the thermopower (which is the parameter, being most sensitive to the impurity concentration). These measurements were made on single-piece Al–Y ingots, before specimens were cut from them. Moreover, it was found that even a small nonuniformity of the Y impurity distribution in Al is stochastic, and it does not correlate with crystallographic plates. After x-ray orientation, specimens were spark cut with a [111] orientation of the long axis. The specimens, having a parallelepiped form were spark cut on an electro-erosion machine tool, which afforded plane-parallelism of their sides, and similarity of their geometry and dimensions. The square cross section of the specimens 1.5 mm × 1.5 mm was measured with a micrometer with an accuracy of up to 0.005 mm. The length between potential probes, which was equal to 12 mm, was determined with an accuracy of up to 0.05 mm. Therefore, the error in the measurements of electrical resistivity, caused by errors in the measurements of the specimen's dimensions, does not exceed 7–8%. Specimens were etched to remove the surface layer, which was deformed during the cutting process, and mounted for electrical measurements.

For the research specimens were chosen with three impurity concentration levels, having the following values of the RRR: 10 200, 7700 and 1600. The RRR was used as a sufficiently exact parameter to characterize the value of impurity concentration in each specimen.

The low-temperature holder, in which it was possible to perform simultaneous measurements on four specimens was developed specially for precise temperature and magnetic field measurements. To decrease the errors in each series of measurements, two specimens of each value of impurity concentration were placed in the holder. From this, during the measurement of specimens with the lowest impurity concentration value (those with RRR = 10 200), together with these specimens were mounted specimens of highly pure (99.9995%) Al single crystals of [111] orientation, with RRR = 14 000, which were used as a primary standard. These measurements methods enabled us to reduce considerably the systematic error and to increase the accuracy of determination of the impurity part of the electrical resistivity.

The electrical measurements were performed by the standard four-probe technique in a transverse magnetic field of a superconducting solenoid up to 8 T and in the temperature range 4.2–30 K. During these measurements the holder with the specimens was placed in a calorstat, and control of the temperature was performed with a gallium arsenide resistance converter, which had thermal contact with the specimens [9]. The temperature measurement error in this temperature range did not exceed 0.1 K. Adjustment and maintenance of the specified values of temperature and magnetic field strength were performed by a computer controlled by a signal from a thermal sensor.

3. Experimental results

The crystallographic orientation of the specimens, specified in the experiment, signifies that during measurements in a transverse magnetic field its vector $\boldsymbol{H}$ lies in the (111) plane. With such geometry of the experiment there was excluded the possibility that the magnetic breakdown effect was exhibited, which is characteristic of aluminium and changes the magnetoresistance behaviour in strong magnetic fields at low temperatures. The above-described arrangement of the experiment made it possible to carry out studies of Al–Y specimens in various magnetic field directions. For Al–Y specimen with RRR = 10 200 the magnetic field was oriented near the [110] crystallographic direction and, for two other specimens with RRR = 7700 and RRR = 1600, the field was deflected from this direction by 15°.

In figures 1–3, experimental results are represented in the form of the temperature dependences of the DMR $\Delta(T)$ at values of the magnetic field strength from 2 to 8 T. It is important to note that for the specimens studied in this H region the high-field limit condition $\omega_c\tau \gg 1$ (where ω_c is the cyclotron frequency and τ the electron relaxation time) was valid. The temperature-dependent DMR $\Delta(T)$ both in the presence of magnetic field and in its absence was traditionally determined as

$$\Delta(T) = (\rho_{\mathrm{imp}}(T, H) - \rho_{\mathrm{imp}}(4.2\ \mathrm{K}, H)) - (\rho_{\mathrm{pure}}(T, H) - \rho_{\mathrm{pure}}(4.2\ \mathrm{K}, H))$$

where ρ_{imp} is the complete electrical resistivity of the metal with impurities and ρ_{pure} is the complete resistivity of the pure metal.

In figure 1 are shown the $\Delta(T)$ dependences of the specimen of RRR = 10 200 for magnetic field values of 0, 2, 4 and 8 T and for the $\boldsymbol{H}$ direction along the [110] axis. As can be observed from the figure, in the absence of a magnetic field the value of the

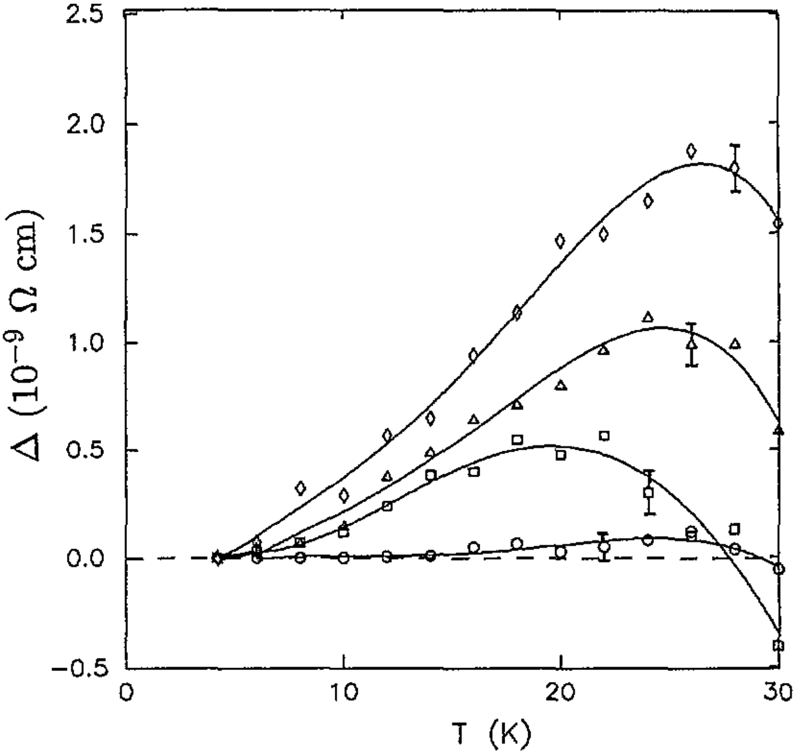

Figure 1. Temperature dependence of the DMR for an Al–Y specimen with RRR = 10200 for various values of the magnetic field: ○, 0 T; □, 2 T; △, 4 T; ◇, 8 T.

DMR is close to zero up to about 15 K, next it increases, achieving a not sharp hump near 25 K, and then it decreases to the region of negative values. The origin of such a weakly expressed $\Delta(T)$ dependence is understandable, if we take into account that the Y impurity concentration in this specimen does not exceed 3×10^{-4} at.%. This situation abruptly changes not qualitatively but quantitatively during the applied magnetic field influence. The hump becomes sharply distinguished, its height increases with increasing field strength, and its position shifts into a higher-temperature region. At $T > 20$–25 K all the curves decrease to the negative-Δ-value region.

The $\Delta(T)$ dependences represented in figures 2 and 3 were measured on specimens with RRR = 7700 and RRR = 1600, respectively, in conditions when H was deflected from the [110] direction by 15°. It is obvious that these curves principally differ from those in figure 1, and this difference is especially clearly expressed in the applied magnetic field. First of all, our attention is drawn to the lack of humps on all the curves in the temperature range researched. The second, somewhat unexpected difference in these results is the negative value of DMR beginning from the lowest temperatures. For this in the region of 4.2–12 K the curves are equidistant from each other and the value of Δ almost does not vary with changes in temperature and magnetic field. With the increase in temperature the value of Δ begins to increase abruptly in the region of negative DMR values and also DMR increases in this region with increase in magnetic field strength.

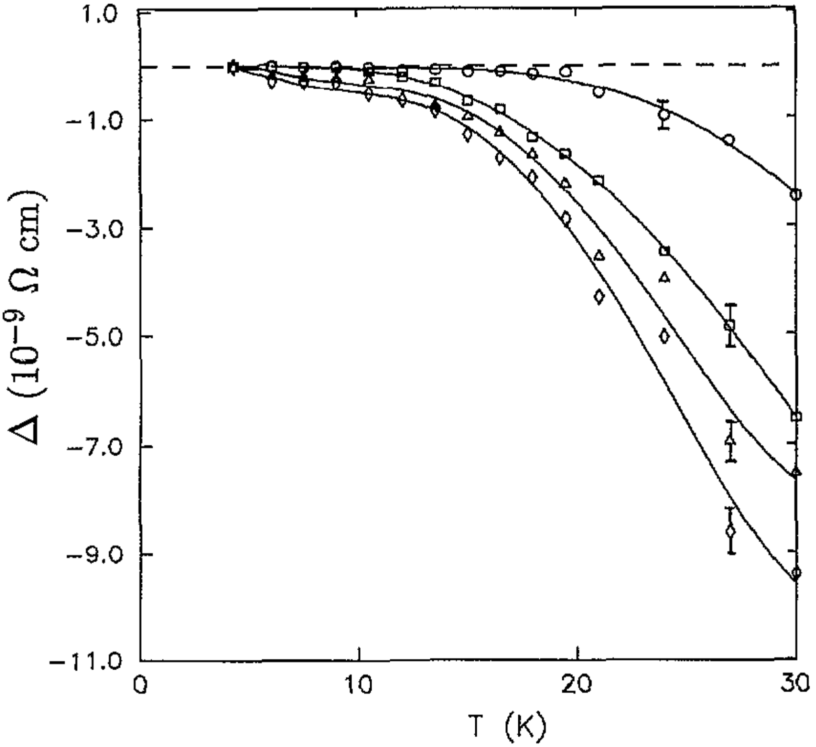

Figure 2. Temperature dependence of the DMR for an Al–Y specimen with RRR = 7700 for various values of the magnetic field: ○, 0 T; □, 2 T; △, 4 T; ◇, 8 T.

4. Discussion

Comparison of the dependences represented in figures 1–3 shows that their qualitative difference is not caused, first of all, by the impurity concentration nor by the magnetic field value. In this case the main cause is the magnetic field direction relative to the crystallographic orientation of specimens. With this distinction in mind an analysis of the experimental results will be made.

In spite of the large number of theoretical models of DMR existing at present, none of them gives an explanation of the DMR for broad ranges of temperatures and impurity concentrations. The most consistent are the theories in which the source of DMR was considered to be the competition between electron scattering mechanisms, one of which increases the anisotropy of the electron distribution function and the other suppresses it [1, 10]. In the present research the increase in the electron distribution function anisotropy may be caused by the electron–phonon scattering processes and its isotropization may be caused by elastic scattering on impurity atoms. In connection with this, the measurements of the DMR in a strong magnetic field are useful, since the anisotropy of the transverse magnetoresistance, existing in the main only in the presence of the electron distribution function, is a peculiar measure of this anisotropy. At present we are aware of only one experimental research study of this kind, which was carried out by Mitchel *et al* [11] on alloyed Al. In this work it was shown that, in a strong magnetic field oriented along the main crystallographic directions of single-crystal specimens the DMR vanishes.

The results of the measurements performed by us in similar conditions and represented

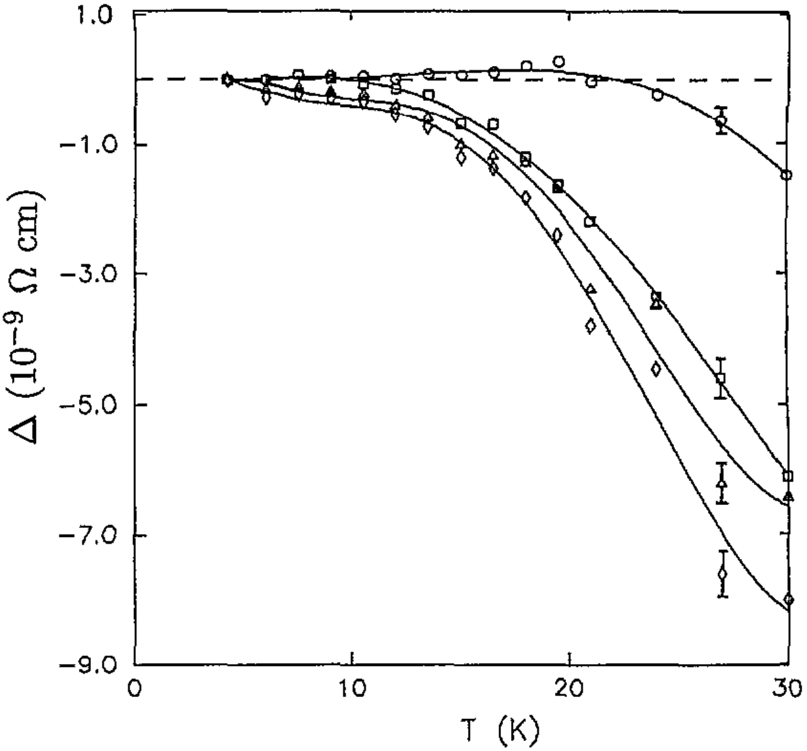

Figure 3. Temperature dependence of the DMR for an Al–Y specimen with RRR = 1600 for various values of the magnetic field: ○, 0 T; □, 2 T; △, 4 T; ◇, 8 T.

in figure 1 contradict the data from [11]. These results bear witness to the presence of a strong DMR, explained by the competition between the anisotropic electron–phonon and isotropic electron–impurity scattering processes. As a result, a hump was observed in the $\Delta(T)$ dependence. An increase in the height of the hump and its shift into a higher-temperature region on increase in the magnetic field strength demonstrates the correlation between the scale of the electron distribution function anisotropy and the magnitude of the DMR.

Qualitatively similar results were obtained and corresponding conclusions were made during the study of the temperature and deformation dependences of the magnetoresistance of pure Al in conditions of anisotropic electron–phonon and electron–dislocation scattering processes, which compete with isotropic processes [12, 13]. Therefore, the main point of the Kagan–Flerov [1] theory is confirmed, where the common nature of the characteristic properties of the behaviour of electrical and galvanomagnetic quantities connected with the particular role of the electron distribution function anisotropy in metals has been shown.

The form of the curves in figure 1 is typical for the $\Delta(T)$ dependences obtained by most authors [2, 3, 7] on polycrystalline specimens of dilute alloys of Al in a broad range of impurity concentrations. The difference in these dependences from the typical ones lies *in the fact that all salient features of these curves (increase in* Δ*, appearance of the hump,* and linear change in the dependence with temperature) are exhibited at temperatures lower than 30 K. In comparison with the data of the preceding work the range of all these salient features exhibition is 'compressed' on the temperature axis from the range 200–250 K to the range 25–30 K. Obviously, this is connected with the low value of Y impurity concentration in Al, the high degree of perfection of the specimens and the magnitude of their RRR. This demonstrates that ascribing a particular DMR model to a specific temperature range is not a correct procedure.

The analysis of the electron–phonon scattering mechanism for the specimen where $\boldsymbol{H}\|[110]$ should be made by comparing the dependences in figures 2 and 3, which are principally different in form from those in figure 1. The absence of humps on these curves enables us to suppose that, in conditions when the magnetic field is oriented not near the main crystallographic directions, the efficiency of anisotropic electron–phonon scattering is not large. From this it is quite natural to consider that electron–impurity scattering is isotropic and does not depend either on the magnetic field value or on its direction. Hence, the particular mechanism of electron–phonon scattering is a factor which determines the difference in the $\Delta(T)$ characteristics.

As is well known, small-angle electron–phonon scattering at low temperatures consists of processes of electron diffusion over the Fermi surface and umklapp processes. In a strong magnetic field the efficiency of umklapp processes can be increased if the field is guided in such a way that electron orbits would pass through the equivalent 'hollows' ('hot spots') on the Fermi surface [5]. This situation takes place in aluminium when at $\boldsymbol{H}\|[110]$ the electron orbits pass through small sections of the Fermi surface in the second zone near W symmetry points. This leads to a sharp increase of the electron distribution function anisotropy and, as a consequence, when there is competition between phonon and impurity scattering processes, a hump appears in the $\Delta(T)$ dependences. If the magnetic field is oriented far from [110] direction (e.g. $\boldsymbol{H}\|[110]+15°$), the diffusion scattering mechanism dominates. As a consequence, the DMR is almost not observed at low temperatures and it becomes an increasing function of temperature for $T > 15$ K.

As was mentioned above, an interesting distinction between the dependences in figures 2 and 3 is not only the absence of humps but also the negative DMR in the whole temperature region, beginning from the lowest temperatures. Dependences of this type were not observed and analysed before, during the study on the impurity part of the resistivity. The possibility of the appearance of a negative DMR was theoretically shown in [14] for electron–dislocation scattering, which for a small dislocation density is substantially small-angle scattering due to the scattering on strength fields of remote action. In our experiment the sources of such remote-action fields may be represented by the regions of dynamic disturbance, the appearance of which is connected with the character of impurity atom oscillations, different from those of matrix atoms. Comparatively long ago such conclusions were made on the results of $\Delta\rho(T, c)$ measurements in Al alloys [15]. For this the larger the difference between the ion radii of the impurity and matrix atoms, the more effective is the influence of these regions on the electron scattering processes. For Al–Y alloys this difference is so large (the ion radius of Y is 2.5 times that of Al) that it could be the reason for the observed negative DMR.

5. Conclusions

Measurements of the temperature dependences of the DMR for Al–Y single crystals related to the impurity concentration, magnitude and direction of magnetic field enable us to make the following main conclusions.

(1) In strong magnetic fields the orientation of the magnetic field relative to the crystallographic geometry of specimen has the main influence on the behaviour of the $\Delta(T)$ dependences.

(2) It is shown that the hump on the $\Delta(T)$ dependence at low temperatures demonstrates the competition between the electron scattering mechanisms, one of which increases the anisotropy of the electron distribution function, and the other suppresses it. For the electron–phonon scattering process of umklapp type, which is effective in conditions when the electron orbits pass through 'hot spots' on the Fermi surface, is anisotropic.

(3) The negative DMR, observed in conditions of diffusive electron–phonon scattering, may be connected with small-angle type of electron scattering in regions of dynamic disturbance, which are determined by the character of oscillations of impurity atoms, differing in size from the matrix ions.

Acknowledgments

We are grateful to Dr E F Golov from the Institute of Pure Metals of the Russian Academy of Sciences (Chernogolovka, Moscow Region) for single crystals of highly pure Al and Al–Y alloys, provided by him for our studies.

The research described in this publication was made possible in part by grant N RW7000 from the International Science Foundation.

References

[1] Kagan Yu and Flerov V N 1974 *Zh. Eksp. Teor. Fiz.* **66** 1374–86 (Engl. Transl. 1974 *Sov. Phys.–JETP* **39** 673–85)
[2] Papastaikoudis C, Papathanasopoulos K, Rocofylou E and Tselfes W 1976 *Phys. Rev.* B **14** 3394–7
[3] Kawata S and Kino T 1974 *J. Phys. Soc. Japan* **39** 684–91
[4] Dosdale T and Morgan G J 1974 *J. Phys. F: Met. Phys.* **4** 402–18
[5] Gurgi R N and Kopeliovich A I 1974 *Zh. Eksp. Teor. Fiz.* **67** 2307–16
[6] Barnard R D 1980 *J. Phys. F: Met. Phys.* **10** 2749–52
[7] Seth R S and Woods S B 1970 *Phys. Rev.* B **2** 2961–72
[8] Alisova S P and Budberg P B 1971 *Itogi Nauki Techniki* **14** 266
[9] Demyanov S E, Drozd A A and Petrovskii M L 1987 *Fiz. Chim. Obrabotki Mater.* **3** 117–9
[10] Jumper W D and Lawrence W E 1977 *Phys. Rev.* **16** 3314–25
[11] Mitchel W, Newrock R S and Wagner D K 1980 *Phys. Rev. Lett.* **44** 426–9
[12] Fickett F R 1971 *Phys. Rev.* B **3** 1941–52
[13] Gostischev V I, Demyanov S E and Sobol' V R 1984 *Fiz. Nizk. Temp.* **10** 994–7
[14] Bergmann A, Kaveh M and Wizer N 1980 *Solid State Commun.* **34** 369–73
[15] Panova G Kh, Zhernov A P and Kutaitsev V I 1967 *Zh. Eksp. Teor. Fiz.* **53** 423–30 (Engl. Transl. 1968 *Sov. Phys.–JETP* **26** 283–91)