Electrotransport and magnetic properties of Cr–GaSb phases synthesized under high pressure

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Abstract
The electrotransport and magnetic properties of new phases in the Cr–GaSb system were studied. The samples were prepared by high-pressure (P = 6–8 GPa), high-temperature treatment and identified by x-ray diffraction and scanning electron microscopy. One of the CrGa₂Sb₂ phases with an orthorhombic structure Iba₂ has a combination of ferromagnetic and semiconductor properties and is potentially promising for spintronic applications. Another high-temperature phase is paramagnetic and identified as tetragonal I₄/mcm.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
In recent years a lot of attention has been given to the search for spintronic materials capable of producing a spin-polarized electric current to carry signals modulated by small external magnetic fields. The problem of the generation of the spin-polarized electric current can be solved in two ways [1]: either by injecting an already polarized current into paramagnetic media or by using the media where a sustained polarized current could exist due to a difference between the density of the states for two spin orientations of carriers (in which case the material must be in the ferromagnetic state). Previously the research effort pursuing the latter goal was limited to searching for diluted magnetic semiconductors (i.e. semiconductors with a small—several per cent—amount of magnetic impurities), resulting in the synthesis of materials with a Curie temperature T_C as high as 170 K in the case of (GaAs)₀.₉₅Mn₀.₀₅ [2, 3]. However, recently the research focus has somewhat shifted to materials for which the theory predicts a full polarization of carriers, such as semiconductors with a zinc-blende structure [4, 5]. For materials with a fully polarized current, the term ‘half-metals’ was coined. CrSb and CrAs provide examples of such materials. Although these materials can be produced as ferromagnetic thin films [6], the study of their properties is hindered by the absence of bulk samples stable at normal conditions. From a practical point of view the potential spintronic devices are layered structures with different functionality of their parts, e.g. including magnetic elements and areas of spin-polarized electric current [7–9]. Nevertheless, the recent developments of spintronic devices using antiferromagnetic [9], ferroelectric [10, 11], and organic-based semiconductor [12] materials as a component part of such a devices, demonstrate that the search of new materials for spintronics is still happening.

Manganese is a popular dopant used for the production of diluted magnetic semiconductors based on the A₃B₅ semiconductor matrix with sphalerite structure. In particular it was used with a GaSb matrix [13, 14]. The use of Cr as a dopant in A₃B₅ semiconductor matrices is much less studied experimentally. Cr-doped GaSb obtained by molecular beam epitaxy [15] is one of the rare examples, though first-principles calculations [16] suggest a ferromagnetic nature of the Cr-based solid solutions with the GaSb matrix. In turn, a comparison of behavior of the relatively close magnetic dopants (e.g. Mn and Cr) in the same semiconductor matrix is of both fundamental and applied importance.

Application of high-pressure synthesis for the production of new materials is motivated by the idea of enhancing the solubility of a magnetic element in a semiconductor
matrix. In the case of GaSb, this idea has been previously realized for non-magnetic and practically insoluble (in GaSb) germanium [17], when a continuous set of diamond-like Ge–GaSb amorphous and crystalline metastable solid solutions has been obtained. Attempts to apply this high-pressure methodology to the Mn–GaSb system have allowed the synthesis in this system of new metastable magnetic phases with high Curie temperatures [18–21].

We have found direct parallels in the high-pressure behavior of Mn–GaSb and Cr–GaSb systems. In particular the synthesized orthorhombic and tetragonal phases in the Cr–GaSb system have nearly the same structure and composition as those in the Mn–GaSb system. It is intriguing that both orthorhombic phases are magnetic, while the tetragonal phase is magnetic only in the case of MnGaSb compound.

It should be noted that manganese is a popular dopant in the production of spintronic materials because, unlike other magnetic atoms (Cr for example), it can much more easily form solid solutions in semiconductor lattices which leads to the formation of diluted magnetic semiconductors. There is still no information on the high-pressure synthesis of zinc-blende type semiconductors with chromium. In this paper we present data on the synthesis of magnetic materials in the Cr–GaSb system under high pressures from 6 to 8 GPa.

2. Synthesis and structure

The samples were obtained by quenching from the synthesis temperatures in the range 700–900 K to room temperature in toroidal anvils [22] under synthesis pressures in the range 6–8 GPa. The initial mixture consists of zinc-blende GaSb and a varying content of Cr in atomic proportion 1:x (i.e. according to the chemical formula Cr$_x$GaSb) where $x = 0.4–1$.

X-ray diffraction measurements of the obtained phases were carried out with a Stoe STADI MP diffractometer device with a Cu K$_\alpha$ radiation source and a curved germanium monochromator. It was found that, depending on the synthesis conditions, two structurally different phases CrGa$_2$Sb$_2$ and Cr–GaSb were recovered with orthorhombic $Iba_2$ (No. 45) [23] and tetragonal $I4/mcm$ (no. 140) [23] space groups, respectively. The synthesis output was generally influenced by the proportion of the initial components and the synthesis temperature, so the higher synthesis temperatures (supposedly above the melting curve or 750–800 K) favor the formation of the latter phase. The diffraction patterns of the two phases are displayed in figure 1. According to x-ray diffraction phase analysis we have obtained two nearly pure phases: orthogonal for the Cr to GaSb proportions 0.5:1 and tetragonal for the proportion 1:1, i.e. the initial compositions correspond to the stoichiometric ones. We consider the presence of possible inclusions below$^4$.

The morphology and chemical composition of the obtained samples were checked after the synthesis using a JEOL electron microscope (see images in figure 2) with an elemental microanalysis function based on an energy dispersive spectrometer. For the orthorhombic phase we present two scanning electron microscopy (SEM) images: the first one (figure 2(a)) is taken from the nearly pure (i.e. stoichiometric) sample and the second one (figure 2(b)) shows a specially chosen area from the non-stoichiometric sample with several Cr grains or their prints. In the image (figure 2(b)) the density of Cr grains exceeds the average over the sample spall. In all cases, the locally dominant (except possible Cr grains) parts of the studied (by SEM) orthorhombic samples were found to correspond to the stoichiometric CrGa$_2$Sb$_2$ composition with an accuracy of 2–4 at.%. In some cases the observed local Cr content in the synthesized samples decreased from $x = 0.5$ down to 0.3, in accordance with the observed admixture of Cr even in the samples with a stoichiometric mixture of initial components. The observed morphology and composition picture for the orthorhombic phase indicates a diffusion mechanism for the formation of this phase. The SEM images taken from the tetragonal Cr–GaSb phase show a quite homogeneous morphology, with a typical picture as presented in figure 2(c). Elemental microanalysis gave a composition close to stoichiometric with systematic excess of the Sb content of several atomic %. Although we observed some

$^4$ When our work was in its final stage we became aware of the synthesis of the high-pressure CrGa$_2$Sb$_2$ phase by Sakakibara et al [24].
Figure 2. SEM images of the high-pressure orthorhombic (a) and tetragonal (c) phases after spalling of the samples. Panel (a) corresponds to the sample synthesized from the stoichiometric (for orthorhombic phase) initial mixture Cr–2GaSb ($x = 0.5$), while panel (b) shows a selected area with Cr grains from the sample with $x = 0.6$. The following areas can be recognized from the elemental analysis in panel (b): A is the prevailing area of the orthorhombic CrGa$_2$Sb$_2$ phase; B is grains of Cr; C is prints left by removed Cr grains on the CrGa$_2$Sb$_2$ phase; and D is the shear of the Cr grain.

small areas with some deviations of content, we did not find a systematic presence of another phase.

It should be stressed that the samples synthesized from stoichiometric mixtures (i.e. $x = 0.5$ for orthorhombic and $x = 1$ for tetragonal phases, respectively) consist practically uniformly of a single phase with point-like precipitates of surplus amounts of initial components. Nevertheless, we observe in the x-ray diffraction pattern of the orthorhombic phase the admixture of Cr (see figure 1(b)) in accordance with SEM data, where we have found an area with deviation of the chromium content to lower values. For a stoichiometric ($x = 1$) tetragonal phase, we observe in the x-ray diffraction pattern (see figure 1(a)) the reflection of unknown phases which have not been identified among known compounds in the Cr–Ga–Sb system. The presence of this phase may be related to systematic deviation of the Sb content to higher values in the tetragonal phase, i.e. the unknown phase may be some Cr–Ga compound. The first attempt to synthesize such a compound in the pure Cr–Ga system was not successful. In any case the amount of Cr or unknown impurities does not exceed 2–5% according to x-ray diffraction intensity estimations.

For both tetragonal and orthorhombic phases a full-profile Rietveld refinement was carried out using Fullprof software [25]. The results are summarized in tables 1 and 2. The respective fits are also shown in figure 1. The agreement factors for these fits are quite good: Bragg’s $R$-factor is 4.43 for the orthorhombic phase and 6.21 for the tetragonal phase, which corroborates structural models suggested in [18, 21, 24]. It should be noted that the space group $I4/mcm$ (CuAl$_2$ type) is quite widespread among dipnictides, for example CrSb$_2$ is crystallized in such a structure [26], so the tetragonal GaSbCr phase can be considered the same structure where Ga atoms arbitrarily substitute the Sb positions.

By using the lattice parameters we estimate the density of the new phases as 6.99 g cm$^{-3}$ (Iba$2$) and 7.3 g cm$^{-3}$ ($I4/mcm$), which is in good agreement with pycnometric densities measured using the same samples ($7.0 \pm 0.02$ and $7.3 \pm 0.02$ g cm$^{-3}$, respectively).

Although no extensive testing of the stability range of the obtained phases has been provided we can conclude from the exothermal step-by-step annealing that both phases are metastable at normal conditions and decompose at room pressure at temperatures above 500 K.

### Table 1. Crystal structure of the orthorhombic phase, space group $Iba2$ (No. 45), $a = 11.772 \pm 0.007 \, \text{Å}$, $b = 5.964 \pm 0.007 \, \text{Å}$, $c = 5.897 \pm 0.007 \, \text{Å}$. Atomic positions, coordinates and site occupancies.

| Cite | X   | Y   | Z   | Occ. |
|------|-----|-----|-----|------|
| Ga   | 8(c) | 0.000 | 0.000 | 1.00 |
| Sb   | 8(c) | 0.000 | 0.000 | 1.00 |
| Cr   | 4(a) | 0.000 | 0.000 | 1.00 |

### Table 2. Crystal structure of the tetragonal phase, space group $I4/mcm$ (No. 140), $a = 6.466 \pm 0.007 \, \text{Å}$, $c = 5.291 \pm 0.007 \, \text{Å}$, $c/a = 0.82$. Atomic positions, coordinates and site occupancies.

| Cite | X   | Y   | Z   | Occ. |
|------|-----|-----|-----|------|
| Ga   | 8(h) | 0.157 | 0.657 | 0.589 |
| Sb   | 8(h) | 0.157 | 0.657 | 0.411 |
| Cr   | 4(a) | 0.000 | 0.000 | 1.000 |
3. Magnetic properties

The magnetic moment was measured with a Quantum Design SQUID magnetometer (fields up to 50 kOe); and sometimes we also used the data obtained with a custom-made inductive device for the ac magnetic susceptibility measurements. The temperature dependence of the spontaneous magnetic moment $M(T)$ was measured in a field of 1 kOe upon heating after zero-field cooling from 250 down to 4.2 K. Magnetic susceptibility was measured in an ac field of the order of 100 Oe. The primary result of this research is the finding of a ferromagnetic ordering in CrGa$_2$Sb$_2$ samples with $Iba_2$ structure. The magnetization curves for the both stoichiometric and non-stoichiometric samples are shown in figure 3. It was found that the Curie temperature $T_C = 350$ K remains almost constant and slightly depends on the initial chromium content. Note that the Curie temperature is substantially higher than the one for MnGa$_2$Sb$_2$ which varies in the range 210–310 K depending on the Mn content [18–21]. In the case of the Mn-based orthorhombic phase we are probably dealing with a set of solid solutions, while the orthorhombic CrGa$_2$Sb$_2$ is more stable with respect to variation of content. On the other hand, an increase in the chromium content up to $x = 0.8$ leads to some smoothing and widening of the ferromagnetic transition as demonstrated in figure 4(a) (compare curve 3 with curves 1 and 2). From the x-ray diffraction and SEM data one can conclude that the increase in initial chromium content results in an increase in the number of Cr grains in the synthesized orthorhombic sample, while the size of the Cr grains remains at the same scale. As seen from figure 3, the spontaneous magnetic moment per Cr atom in the samples with higher chromium content ($x = 0.6$) is below 1 $\mu_B$ at room temperature, which is slightly lower than in the stoichiometric phase. This discrepancy can be attributed to the fact that the excess amount of chromium may form antiferromagnetic precipitates in a ferromagnetic bulk sample, resulting in an apparent decrease in the magnetic moment. With a decrease in temperature, the spontaneous magnetic moment increases up to 1.0 $\mu_B$ per Cr atom at helium temperature which is accompanied by an increase in the magnetic coercive force (figure 3). The coercivity of the orthorhombic phase is quite high (2500 Oe at 77 K and 600 Oe for nonstoichiometric phase at 290 K, see figure 3) and is sensitive to the impurity concentration.

5 Previously this phase in [18–20] was erroneously identified as a simple cubic structure.
Unlike an analogous compound with manganese, the $I4/mcm$ phase Cr–GaSb has no magnetic ordering and is paramagnetic in the temperature range $T = 4.5–300$ K, as can easily be concluded from the data in figure 5.

4. Electrotransport properties

The electrical resistance of the new Cr–GaSb phases, measured by the four-probe method, is much higher than that of the analogous manganese-based phases. Even the resistance of the metallic $I4/mcm$ phase (see the inset in figure 5) is almost an order of magnitude higher than the values reported in [19] for the tetragonal phase Mn–GaSb. The electrical resistance of the orthorhombic phase is a more complicated point because the bulk resistance of a pure phase can be shunted by inclusions of metallic chromium or conductive amorphous phases of GaSb as well as by contamination with a tetragonal phase. This may explain the observed decrease in the conductivity of $Iba2$ phases CrGa$_2$Sb$_2$ with the chromium content deviating from stoichiometric (see figure 6). So we may consider the resistivity of the stoichiometric phase (figure 6, curve 1) to be intrinsic, while the deviation observed in curves 2 and 3 (figure 6) may be attributed to impurities. A small decrease of resistivity in the temperature range $T = 4.2–8.0$ K observed for the tetragonal phase (see inset in figure 5) can also be attributed to impurities of amorphous GaSb as well as to gallium itself which, under certain conditions, can display superconducting properties [27].

The temperature dependence of resistivity of the orthorhombic phase can be divided into two temperature regions: the first one is above 250–290 K where the temperature dependence is similar to the semiconducting one (i.e. increasing with decreasing temperature), and the second region is below these temperatures where the resistance is an increasing function of temperature. The transport properties of the orthorhombic phase below $T_C$ can be compared with the transport properties of ‘dirty’ metals with strong impurity scattering. However, in the case of CrGa$_2$Sb$_2$ (unlike MnGa$_2$Sb$_2$, as observed in [21]) there is no straightforward correspondence between the Curie temperature and the cusp in the resistivity curve, the temperature dependence of resistivity changes the trend at much lower temperatures than the temperature where the ferromagnetic ordering takes place (290 K and 350 K, respectively).

This transition from semiconducting to metallic behavior can be compared with those in EuO [28] and GdN [29, 30], though in these cases the metal–insulator transition is more pronounced with resistivity drop spanning an order of magnitude of $10^8$. In our case quite moderate change of the resistivity and a less sharp transition can be attributed to the narrower energy gap (which is equal to 1.2 eV in EuO and 0.9 eV in GdN) and the possible influence of intragap states giving rise to weak localization effects. This type of interaction is also considered in the literature as a possible cause leading to attenuation of the metal–insulator transition with the variation in impurity concentration [31, 32].
5. Discussion and final remarks

Better insight into the electronic state of both phases can be gained by comparing the observed resistivity with a calculated ‘minimal metallic’ conductivity expected for these phases. Taking into account the lattice parameters, the upper limit for the conductivity of the metallic state can be obtained with the assumption that a unit cell (of volume \( V \)) contributes to the conduction band one carrier with a scattering length equal to the shortest of lattice parameters (\( \lambda \)):

\[
\sigma_{\text{min}} = \frac{(3\pi^2)^{2/3}(e^2/\hbar)}{\lambda^{2/3}}. \tag{1}
\]

The calculation according to the above formula yields the values \( \rho_{\text{max}} = 1/\sigma_{\text{min}} = 3.7 \times 10^{-3} \Omega \text{ cm} \) and \( \rho_{\text{max}} = 2.7 \times 10^{-3} \Omega \text{ cm} \) for the orthorhombic and tetragonal phases, respectively. This means that the tetragonal phase is almost on the verge of a metal–insulator transition while the orthorhombic phase is in the semiconducting state with the presence of conductive inclusions in the samples. This indicates that the impurities do increase the measured conductivity of the samples though the measured conductivity of the samples though value of the conductivity is still well below \( \sigma_{\text{min}} \).

Although the measurements we have carried out could not provide information about polarization of carriers in the samples, we believe that the CrGa\(_2\)Sb\(_2\) compound may prove to be an interesting candidate for spintronic applications because of its fairly high Curie temperature and semiconducting properties.

It is appropriate to compare the high-pressure behavior of the Gr–GaSb system with that of the Mn–GaSb system [18–21] in more detail. As we noted previously, there are direct parallels in the high-pressure behavior of Mn–GaSb and Cr–GaSb systems, when we consider structure of the synthesized orthorhombic and tetragonal phases and conditions for their synthesis (here, we mean temperature intervals at pressures of 6–8 GPa). It is intriguing that the replacement of Mn by Cr in the orthorhombic phase results in an increase in the Curie temperature, while for the metallic tetragonal phases such a replacement results in a transition from the stronger (with respect to the orthorhombic phase) ferromagnetic to the paramagnetic. Another remarkable difference of the Cr- and Mn-based systems concerns the orthorhombic phase, when it is synthesized with non-stoichiometric composition of initial components (the metal and GaSb). In the case of the Mn–GaSb phase, variation of the composition of the initial components resulted in variation of the Curie temperature (the orthorhombic phase) by 50 K [20]. For Cr–GaSb we do not observe this shift, and the Curie temperature is not influenced by the changes in the initial composition. This indicates that the orthorhombic CrGa\(_2\)Sb\(_2\) compound is much more stable than the MnGa\(_2\)Sb\(_2\) analog with respect to the disturbance of the transition metal (Cr or Mn) subsystem, including point defects, deficit or additional solubility of the metal atoms.

Comparing our structural study of the orthorhombic CrGa\(_2\)Sb\(_2\) phase with similar results recently published [24], we can see that structural parameters from the Rietveld refinements for the orthorhombic phase (table 1) are very close. In particular, the differences in the lattice parameters are nearly 0.1%. The coordinates of Sb atoms (which are the largest in this system) are also quite close. Taking into account that there are differences in the preparation method (multi-cycling in [24] and single-cycling here), the closeness of structural parameters correlates with the above-mentioned stability of the orthorhombic CrGa\(_2\)Sb\(_2\) phase with respect to disturbance of the Cr subsystem. On the one hand, one can find the Z coordinates of Ga atoms from [24] and we can see that structural parameters from the Rietveld refinements for the orthorhombic phase (table 1) and from the current study differ by 10%. This difference is probably related to an influence of the Cr subsystem (sublattice) formed as linear chains along Z axes. In our case, the local Cr content can be more dispersed, implying a deficit or additional solubility of the Cr atoms. In our case, for the stoichiometric samples (\( x = 0.5 \)) a deficit of Cr in local areas is more probable, as follows from the SEM experiments and the presence of small admixtures of pure Cr in the samples.

Comparing the magnetic data for the orthorhombic phase with those from [24], one can indicate that the saturation magnetic moment reported there extrapolated to 0 K is equal to 1.6 \( \mu_B/\text{Cr} \) atom, while in our case this value for the sample with \( x = 0.5 \) can be estimated from figures 3 and 4 as 1.35 \( \mu_B/\text{Cr} \) atom. This is also indicative of some deficit of Cr in the orthorhombic phase.

Finally, one can note that new high-pressure experiments with systems including the transitional metal and \( A^3B^5 \) semiconductor may be promising for the synthesis of new ferromagnetic compounds and, in particular, ferromagnetic semiconductors.

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References

[1] Fert A 2008 Nobel lecture: origin, development, and future of spintronics Rev. Mod. Phys. 80 1517–30
[2] MacDonald A H, Schiffer P and Samarth N 2005 Ferromagnetic semiconductors: moving beyond (Ga, Mn)As Nature Mater. 4 195
[3] Dietl T 2002 Ferromagnetic semiconductors Semicond. Sci. Technol. 17 377
[4] Shirai M 2003 Possible half-metallic ferromagnetism in zinc blende CrSb and CrAs (invited) J. Appl. Phys. 93 6844–6
[5] Bose S K and Kudrnovský J 2010 Exchange interactions and Curie temperatures in Cr-based alloys in the zinc blende structure: volume- and composition-dependence from first-principles calculations Phys. Rev. B 81 054446
[6] Li S, Lu L and Huang Z 2007 Ferromagnetic CrSb film fabricated by pulse-laser deposition and rapidly annealing J. Magn. Magn. Mater. 312 305–9
[7] Žutić I, Fabian J and Das Sarma S 2004 Spintronics: fundamentals and applications Rev. Mod. Phys. 76 323–410
[8] Dash S P, Sharma S, Patel R S, de Jong M P and Jansen R 2009 Electrical creation of spin polarization in silicon at room temperature Nature 462 491–4

[9] Park B G et al 2011 A spin-valve-like magnetoresistance of an antiferromagnet-based tunnel junction Nature Mater. 10 347–51

[10] Khitun A, Nikonov D E and Wang K L 2009 Magnetoelectric spin wave amplifier for spin wave logic circuits J. Appl. Phys. 106 12

[11] Garcia V et al 2010 Ferroelectric control of spin polarization Science 327 1106–10

[12] Yoo J-W, Chen C-Y, Jang H W, Bark C W, Prigodin V N, Eom C B and Epstein A J 2010 Spin injection/detection using an organic-based magnetic semiconductor Nature Mater. 9 638–42

[13] Chen X et al 2002 Above-room-temperature ferromagnetism in GaSb/Mn digital alloys Appl. Phys. Lett. 81 511–3

[14] Abe E, Matsukura F, Yasuda H, Ohno Y and Ohno H 2000 Molecular beam epitaxy of III–V diluted magnetic semiconductor (Ga, Mn)Sb Physica E 7 981–5

[15] Abe E, Sato K, Matsukura F, Zhao J H, Ohno Y and Ohno H 2004 Molecular beam epitaxy and properties of Cr-doped GaSb J. Supercond. 17 349–52

[16] Uspenskii Yu A and Kulatov E T 2009 Ab initio calculation and analysis of the properties of digital magnetic heterostructures and diluted magnetic semiconductors of IV and III–V groups J. Magn. Magn. Mater. 321 931–4

[17] Brazhkin V V, Lyapin A G, Popova S V and Kalyaeva N V 1995 Preparation of a new class of semiconductors: bulk amorphous tetrahedral solid solutions Ge1−x(GaSb)x J. Mater. Sci. 30 443–6

[18] Popova S, Sazanova O, Brazhkin V, Kalyaeva N, Kondrin M and Lyapin A 2006 High-pressure phases in the GaSb–Mn system Phys. Solid State 48 2177–82

[19] Kondrin M V, Popova S V, Gizatullin V R, Sazanova O A, Kalyaeva N V, Lyapin A G, Brazhkin V V, Gudoshnikov S A and Prokhorova Yu V 2006 Ferromagnetism in the high-pressure phases of (GaSb)1−xMn JETP Lett. 84 195–8

[20] Kondrin M V, Popova S V, Gizatullin V R, Sazanova O A, Kalyaeva N V, Lyapin A G, Brazhkin V V, Pronin A A, Gudoshnikov S A and Prokhorova Yu V 2008 Electrotransport and magnetic properties of metastable phases in the system GaSb–Mn synthesized under high pressure J. Phys.: Conf. Ser. 121 032011

[21] Sakakibara W, Hayashi Y and Takizawa H 2009 MnGa2Sb2, a new ferromagnetic compound synthesized under high pressure J. Ceram. Soc. Japan 117 72–5

[22] Khvostantsev L G, Slesarev V N and Brazhkin V V 2004 Toroid type high-pressure device: history and prospects High Press. Res. 24 371–83

[23] Hahn T (ed) 2002 International Tables for Crystallography 5th edn, vol A (Dordrecht: Kluwer)

[24] Sakakibara W, Hayashi Y and Takizawa H 2010 High-pressure synthesis of a new ferromagnetic compound, CrGa2Sb2 J. Alloys Compounds 496 L14–7

[25] Rodriguez-Carvajal J 1993 Recent advances in magnetic structure determination by neutron powder diffraction Physica B 192 55–69

[26] Takizawa H, Yamashita T, Uheda K and Endo T 2001 High pressure crystal chemistry of transition metal diantimonides Phys. Status Solidi b 223 35–9

[27] Demishev S V, Kosichkin Yu V, Lunts D G, Sluchanko N E and Lyapin A G 1992 Critical behavior of the conductivity of a medium with superconducting inclusions JETP Lett. 56 44–8

[28] Shapira Y, Foner S and Reed T B 1973 EuO. I. Resistivity and Hall effect in fields up to 150 kOe Phys. Rev. B 8 2299–315

[29] Granville S et al 2006 Semiconducting ground state of GdN thin films Phys. Rev. B 73 235335

[30] Leuenberger F, Parge A, Felsch W, Fauth K and Hessler M 2005 GdN thin films: bulk and local electronic and magnetic properties Phys. Rev. B 72 014427

[31] Sinjukow P and Nolting W 2004 Fully self-consistent determination of transport properties in Eu-rich EuO Phys. Rev. B 69 214432

[32] Arnold M and Kroha J 2008 Simultaneous ferromagnetic metal–semiconductor transition in electron-doped EuO Phys. Rev. Lett. 100 046404