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ФОРМИРОВАНИЕ ЭПИТАКСИАЛЬНЫХ ПЛЕНОК InSb НА ПОЛУИЗОЛИРУЮЩЕМ GaAs(100) МЕТОДОМ ВЗРЫВНОГО ТЕРМИЧЕСКОГО ИСПАРЕНИЯ: ИХ СТРУКТУРА И ЭЛЕКТРИЧЕСКИЕ СВОЙСТВА

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Исследованы фазовый состав, кристаллическое совершенство и электрические свойства пленок антимонида индия (InSb), обусловленные температурой их осаждения на подложки полуизолирующего GaAs(100). Методом взрывного термического осаждения порошка InSb на подложки полуизолирующего GaAs(100) в интервале температур 375–460 °C были сформированы тонкие пленки InSb различной степени кристаллического совершенства. Рентгеноструктурным анализом установлено, что пленки InSb являются гетероэпитаксиальными. Показано, что увеличение температуры осаждения от 375 до 460 °C приводит к изменению шероховатости (R_a) поверхности пленок от 3,4 до 19,1 нм. Чувствительность электродвижущей силы Холла к магнитному полю пленок InSb меняется в диапазоне 500–1500 мВ/Тл. Концентрация электронов (n) и их подвижность (μ) колеблются в интервале $2 \cdot 10^{16} - 6 \cdot 10^{16}$ см$^{-3}$ и $10 \cdot 10^3 - 21 \cdot 10^3$ см^2/(В · с). Сформированные на подложке полуизолирующего GaAs(100) пленки InSb представляют практический интерес для изготовления высокочувствительных миниатюрных преобразователей Холла.

Ключевые слова: антимонид индия; пленка; подложка; вакуумное осаждение; структура; электрические свойства.

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FORMATION OF EPITAXIAL InSb FILMS ON SEMI-INSULATING GaAs(100) BY EXPLOSIVE THERMAL EVAPORATION: THEIR STRUCTURE AND ELECTRICAL PROPERTIES

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In the present work, the influence of the deposition temperature of InSb films on semi-insulating GaAs(100) on their phase composition, crystal perfection and electrical properties was investigated. The InSb films of various extent of crystal perfection are formed by means of explosive thermal deposition of InSb on semi-insulating GaAs(100) substrates in the temperature range of 375–460 °C. X-ray diffraction analysis established that the films are heteroepitaxial. It is shown that an increase in the deposition temperature of InSb films from 375 to 460 °C leads to a change in the film surface roughness (R_a) from 3.4 to 19.1 nm. The Hall voltage sensitivity to the magnetic field of InSb films varies in the range of 500–1500 mV/T. The electron concentration (n) and mobility (μ) changes in the range of $2 \cdot 10^{16} - 6 \cdot 10^{16}$ cm^{-3}, $10 \cdot 10^3 - 21 \cdot 10^3$ cm^2/(V · s). The formed InSb films on semi-insulating GaAs(100) substrate are of practical interest for the manufacture of highly sensitive miniature Hall devices.

Keywords: indium antimonide; film; substrate; vacuum deposition; structure; electrical properties.

Introduction

Indium antimonide (InSb) is a narrow-band straight-gap semiconductor of the $A^{III}B^{V}$ group with an energy gap of 0.18 eV at 300 K, which has a record high electron mobility. Due to its properties, InSb is widely used in the field of microelectronics. Based on InSb, highly sensitive photocells, Hall sensors, magnetoresistors, and optical filters are manufactured. InSb is also used in infrared detectors, including thermal imaging.

Methods of deposition of semiconductor films make it possible to give them various types of structural perfection, from polycrystalline to epitaxial structure, depending on the deposition conditions and the structure of the substrate. The first work on the preparation of InSb films on various types of substrates appeared in the middle of 1950s. The research results of this period are presented, for example, in works [1–3]. The most used crystalline material for epitaxial growth of InSb is GaAs. However, lattice mismatch between InSb and GaAs is quite large and amounts to ~14 %. Therefore, the formation of epitaxial perfect InSb films is a complex scientific and technological goal. At the moment, the exact mechanisms and models of epitaxial growth of InSb on GaAs depending on the deposition conditions are not established. The high quality epitaxial InSb films on single-crystal substrates are formed by molecular beam epitaxy (MBE) [4; 5]. The two-stage processes of InSb deposition by MBE in the deposition temperature range of 300–390 °C were the most successful, which made it possible to create epitaxial InSb films on GaAs(111) of sufficient perfection confirmed by results of their electrical properties measurements. Other methods used to create InSb films, such as the three-temperature method and electron beam evaporation do not allow to form the films with the exact stoichiometry of the InSb compound and sufficient adhesion of the film to the substrate for further practical application [6–8].

The deposition of InSb films on GaAs by explosive thermal evaporation makes it possible to achieve high values of the film deposition rate. However, the epitaxial growth of thin InSb films on GaAs during explosive thermal evaporation is a rather complicated process, depending on the substrate temperature, the temperature of the powder evaporator, the size of the powder, its purity, and the rate of powder supply to the evaporator [9; 10].

The aim of this work is to find the regularities of the changes in the phase composition, structure and microcrystalline structure, electrical properties of InSb films on GaAs(100) during explosive thermal evaporation deposition depending on deposition temperature (375–460 °C). The choice of a higher temperature interval in heating the substrate during explosive evaporation in relation to MBE is a consequence of the higher deposition rate, which is a feature of the method we use.

Preparation and experimental details

InSb films on semi-insulating single-crystal GaAs(100) substrates deposited by explosive thermal evaporation of a single-crystal InSb powder were investigated [11]. Powder made of InSb single crystal with a carrier concentration of 10^{15}–10^{16} cm^{-3} was used for film deposition. The films were deposited in vacuum ($5 \cdot 10^{-3}$ Pa) through masks to give the sample a rectangular shape with contact pads. The temperature of the substrate holder with the GaAs plate was varied by means of a heater in the range from (375 ± 2.5) to (460 ± 2.5) °C.

During the experiment, the temperature of the GaAs substrate was controlled by a thermocouple. The thickness and the deposition rate of the film was monitored by a quartz sensor. The thickness of formed film was measured on a profilometer using a Mahr MarSurf M400 (Germany). The measured film thickness (d) was (2.0 ± 0.05) μm.

Crystal state of the formed films was investigated by the X-ray diffraction (XRD) analysis with CuK_α radiation using a Rigaku Ultima IV diffractometer (Japan). The microstructure and element composition of the deposited films was analysed on a scanning electron microscope (SEM) using a LEO 1455VP (*Carl Zeiss*, Germany). The roughness of the film surface was estimated using a Solver P47-Pro atomic force microscope (*NT-MDT*, Russia).

The electrical properties (electrical resistivity and Hall effect) using a four-contact method on rectangular samples were investigated [12]. Hall measurements were performed in a magnetic field of (0.44 ± 0.01) T. The electric current value was (10.0 ± 0.1) mA. The estimated error in measuring the concentration (n) and mobility (μ) of charge carriers does not exceed 7 %. The Hall voltage sensitivity to the magnetic field of InSb films was calculated from the following equation [13]:

$$\gamma = \frac{U_{\mathrm{Hmax}}}{B},$$

where U_{Hmax} is the Hall maximum voltage; B is the magnetic induction.

Results and discussion

The results of the XRD analysis of the phase composition of films on semi-insulating GaAs(100) formed by explosive thermal evaporation of InSb powder as a function of the substrate temperature in the temperature range of 375–460 °C are displays in fig. 1.

From the XRD patterns presented in fig. 1 and their analysis using the ICDD-PDF2 database, it follows that in the temperature range of 375–460 °C, the phase composition of the films is an InSb compound. Note that the diffraction reflection from a single-crystal GaAs(400) substrate was recorded in the region of a diffraction angle of 66°. The intensity of the diffraction GaAs line is many times higher than the intensities of the InSb line, which prevents the correct perception of the XRD patterns. Therefore, reflection GaAs(400) is not shown on it. The reflection from the crystallographic planes (400) and (100) are structurally equivalent. Diffraction reflections from the plane (100) for InSb and GaAs have a small diffraction angle and are not observed experimentally in the XRD pattern. The angular positions for diffraction from the plane (400) correspond to diffraction from four interplanar distances (100). They are experimentally recorded on the XRD pattern and indicated in the ICDD-PDF2 database.

The InSb films have a prevalent orientation (100), which repeats the orientation of the single-crystal GaAs substrate (100), since the intensity of the InSb(400) diffraction peak is many times higher than the intensities of other InSb peaks (see fig. 1). The maximum intensity of the InSb(100) diffraction peak is observed at a film deposition temperature of 440 °C. Consequently, the InSb films deposited in the temperature range of 375–460 °C are heteroepitaxial. In addition, with an increase in the substrate temperature, diffraction reflections from the (111), (220), and (311) crystallographic planes were observed. This is due to the formation and increase in the concentration of intercrystalline boundaries with an increase in the deposition temperature. At a deposition temperature of 460 °C, the intensity of diffraction peaks from planes (111), (220), and (311) is greatest.

Note that an increase in the GaAs substrate temperature during the deposition of InSb films from 375 to 460 °C leads to an increase in the film roughness (fig. 2). The average roughness (R_a) for the sample formed at deposition temperatures of 375 °C is 3.4 nm, while for the sample formed at deposition temperature of 460 °C is 19.1 nm. An increase in the deposition temperature leads to an increase in the crystallite size of the InSb film, as a result of the coalescence of smaller crystallites [10], which leads to an increase in the surface roughness.

The electrical properties of InSb films on GaAs(100) formed by explosive thermal evaporation, depending on the substrate temperature, are presented in the table.

**Electrical properties of InSb films formed on GaAs(100)
by explosive thermal evaporation depending on the substrate temperature**

Deposition temperature, °C	γ, mV/T	n, cm^{-3}	μ, cm^2/(V · s)
375	568.18 ± 0.03	(5.4 ± 0.5) · 10^{16}	(21 ± 2) · 10^3
430	1159.09 ± 0.03	(2.6 ± 0.3) · 10^{16}	(12.0 ± 1.0) · 10^3
440	1477.27 ± 0.03	(2.1 ± 0.4) · 10^{16}	(11.0 ± 1.0) · 10^3
460	931.81 ± 0.03	(3.3 ± 0.3) · 10^{16}	(9.8 ± 0.9) · 10^3

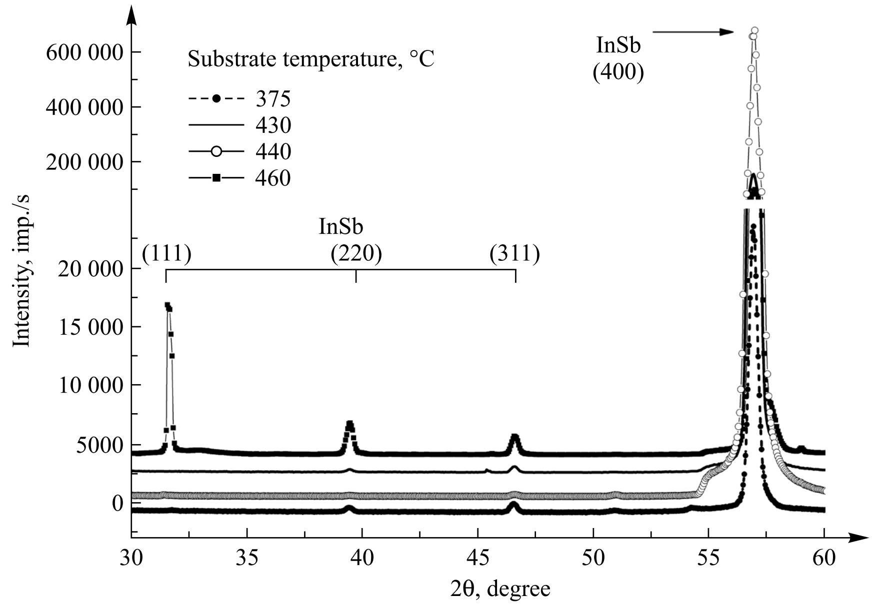

Fig. 1. XRD patterns of films samples deposited on semi-insulating GaAs substrates by explosive thermal evaporation of InSb powder as a function of the substrate temperature

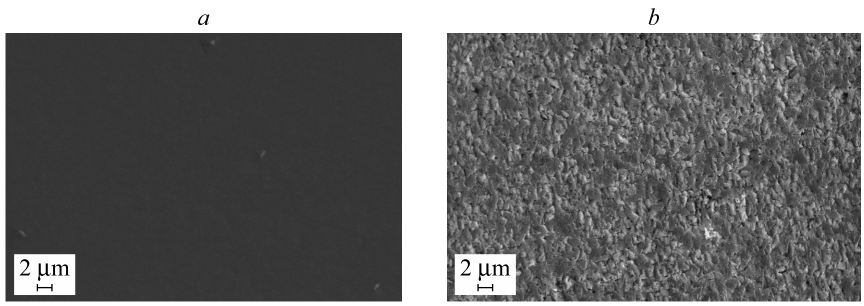

Fig. 2. Scanning electronic images of the surface of InSb films formed by explosive thermal evaporation at deposition temperatures: *a* – 375 °C; *b* – 460 °C

In InSb thin films, independent of their preparation method, the mobility of carriers charge depends strongly on the thickness of film, especially at $d < 2–3$ μm [14]. This is due to the presence of a defect transition layer between the substrate and the film. An increase in the film thickness leads to a decrease in the density of misfit dislocations at the film-substrate interface, the presence of which is due to the difference in the lattice parameters of InSb and GaAs. At the same time, an increase in the crystallite size is observed, which in turn leads to a decrease in the scattering of charge carriers at grain boundaries [9].

The data in the table show that in the substrate temperature range of 375–460 °C, InSb films on GaAs formed by explosive thermal deposition have different electrical properties. With an increase in the deposition temperature from 375 to 460 °C, the mobility of charge carriers decreases by a factor of two. This is due to the scattering of carriers by inhomogeneities due to an increase in the concentration of grain boundaries at higher deposition temperatures. Epitaxial films have the Hall voltage sensitivity to the magnetic field of InSb films varies in the range of 500–1500 mV/T. At the same time, similar Hall devices known today have a sensitivity to the magnetic field of 300–500 mV/T [15]. The electron concentration in the range of $2 \cdot 10^{16} – 6 \cdot 10^{16}$ cm^{-3}.

The changes in the extent of crystal perfection of the films presented above have a significant effect on their electrical resistivity. At a deposition temperature of 375 °C, the film electrical resistivity is $2 \cdot 10^{-5}$ Ω · m, while at a deposition temperature of 460 °C the continuity of the film is disrupted and its electrical resistivity increases to $8 \cdot 10^{-5}$ Ω · m. The increase in electrical resistivity with the increase in the substrate temperature is due to the decrease in mobility of the charge carriers as a result of decrease in the preferred orientation and appearance of additional crystallite orientations in the film. The resistance of InSb films deposited on GaAs(100) by explosive thermal evaporation depending on the deposition temperature are shown in fig. 3.

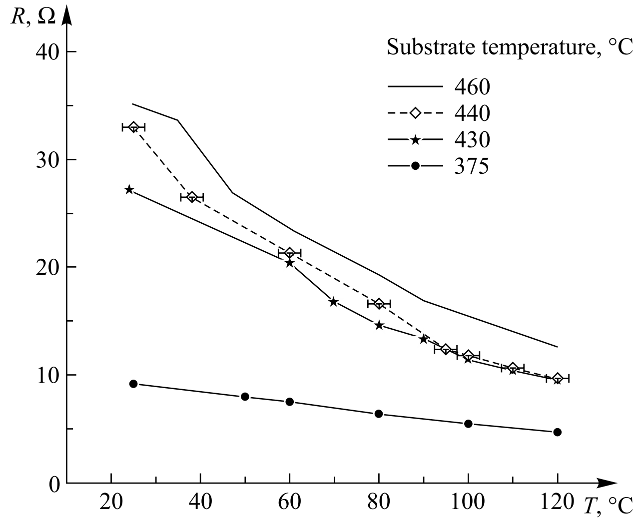

Fig. 3. Temperature dependence of resistance (*R*) of the InSb films on semi-insulating GaAs(100) substrates deposited by explosive thermal evaporation at different substrate temperatures

The obtained temperature dependence of the resistance satisfies the properties of semiconductor materials, i. e. as the temperature rises, the resistance decreases. At the films deposition temperatures of 430–460 °C, the change in resistance with increasing temperature is more significant (see fig. 3). For the film, the deposition temperature of which is 375 °C, the drop in resistance with an increase in temperature by 100 °C is 3 Ω, while for the film obtained at a deposition temperature of 460 °C, this value is more than 20 Ω.

Conclusions

The explosive thermal evaporation method is promising for obtaining InSb films. The advantage of the method is its technical implementation in comparison with MBE. The high deposition rate of the films makes it possible to reduce the cost of devices based on them. In addition, a high repeatability of the results on the concentration and mobility of carriers, homogeneity and phase composition of the grown films is observed.

In this investigation, it was found that the heteroepitaxial InSb films of various extent of crystal perfection are formed by means of explosive thermal deposition of InSb on semi-insulating GaAs(100) substrates in the temperature range of 375–460 °C. The Hall voltage sensitivity to the magnetic field of InSb films varies in the range of 500–1500 mV/T. The electron concentration and mobility changes in the range of $2 \cdot 10^{16} - 6 \cdot 10^{16}$ cm^{-3} and $10 \cdot 10^{3} - 21 \cdot 10^{3}$ $cm^{2}/(V \cdot s)$, respectively. The formed InSb films on semi-insulating GaAs(100) make it possible to use them as highly sensitive miniature Hall devices.

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