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SEMICONDUCTOR STRUCTURES, LOW-DIMENSIONAL SYSTEMS, AND QUANTUM PHENOMENA

Electrical and Optical Properties of Unrelaxed $InAs_{1-x}Sb_x$ Heteroepitaxial Structures

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Abstract—The electrical and galvanomagnetic properties of unrelaxed heteroepitaxial $InAs_{1-x}Sb_x$ structures ($x = 0.43$ and 0.38) in a wide temperature range of 5–300 K and magnetic fields up to 8 T are studied. From the thermal-activation dependence of the electrical conductivity, the band gap of the composition $InAs_{0.57}Sb_{0.43}$ is estimated as 120 meV. The electron concentration in $InAs_{1-x}Sb_x$ (6×10^{16} cm^{-3} for $InAs_{0.62}Sb_{0.38}$ and 5×10^{16} cm^{-3} for $InAs_{0.57}Sb_{0.43}$) determined from the Hall effect agrees well with the electron concentration calculated from the Shubnikov–de-Haas oscillations. We also carry out the spectral ellipsometric studies of unrelaxed heteroepitaxial structures of $InAs_{1-x}Sb_x$ ($x = 0.43$ and 0.38) in the photon energy range of 1–6 eV. The spectral dependences of the imaginary and real parts of the dielectric constant are determined. The dispersion dependences of the refractive index and the extinction coefficient are calculated and presented.

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1. INTRODUCTION

Materials based on solid solutions of the III–V Group capable of absorbing and emitting light in the technologically important spectral region from 3 to 12 μm, into which the atmospheric transparency windows fall, are promising materials for infrared technology. The most suitable for practical use are solid solutions of $InAs_{1-x}Sb_x$, which have the unique property of a wide range of variation in the band gap on compositions (on the value of x) falling within the specified spectral region.

In the previous article [1], we described in detail the method for obtaining heteroepitaxial structures and their characterization by high-resolution X-ray diffraction, scanning atomic-force microscopy, and micro Raman scattering. It was shown that unrelaxed layers of the $InAs_{1-x}Sb_x$ solid solution were obtained by molecular-beam epitaxy using GaInSb and AlGaInSb graded buffer layers. The purpose of this study is to investigate the electrical and optical properties of $InAs_{1-x}Sb_x$ heteroepitaxial structures ($x = 0.43$ and 0.38).

2. ELECTRICAL AND GALVANOMAGNETIC STUDIES

We investigated the electrical conductivity in a wide temperature range of 5–300 K by the standard four-probe method with a selective technique at the frequency of 20.5 Hz using a Lock in Amplifier SR 905. Point contacts were deposited with silver paste. A magnetic field was generated by a superconducting solenoid, the samples were placed at its center, and the highest magnetic field achieved was 8 T. The current did not exceed 1 mA to prevent sample overheating. In Fig. 1, we show the temperature dependence of the resistivity ρ of an $InAs_{0.57}Sb_{0.43}$ sample in the temperature range $T = 5$–300 K in Arrhenius coordinates. The thermal-activation character of the temperature dependence of the resistivity in the 300–100 K region, which is characteristic of the intrinsic conductivity, is clearly seen:

$$\rho = \rho_0 e^{\Delta T/2kT}, \tag{1}$$

the resistivity of the film increases exponentially as the temperature decreases. Here ΔE is the band-gap width. Estimates of the band gap from Eq. (1) give a value of $\Delta E \approx 120$ meV, which agrees satisfactorily with the photoluminescence measurements of $InAs_{1-x}Sb_x$ solid solutions [2]. The observed plateau in the temperature range of $T < 100$ K in Fig. 1 is due to the fact that the increase in the resistivity is shunted by the lower-resistance underlying layers of the heteroepitaxial structure.

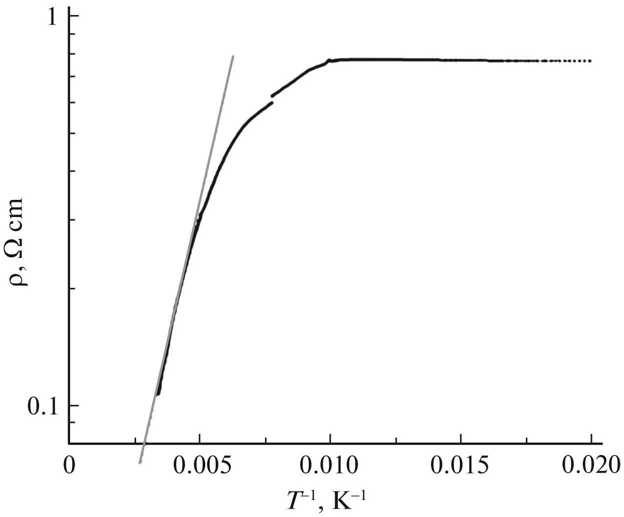

Fig. 1. Temperature dependence of the resistivity of the $InAs_{0.57}Sb_{0.43}$ sample in the range of 5–300 K.

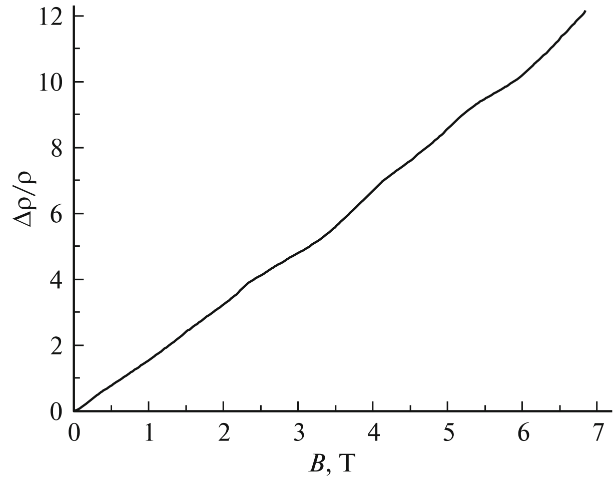

Fig. 2. Magnetic-field dependence of the resistivity in the $InAs_{0.57}Sb_{0.43}$ samples at a temperature of $T = 5$ K.

Investigations of the Hall effect showed that all samples had n-type conductivity. The electron concentration estimated from the field dependence of the Hall voltage for $InAs_{0.62}Sb_{0.38}$ turned out to be $n = 6 \times 10^{16}$ cm^{-3}. For the $InAs_{0.57}Sb_{0.43}$ composition, the electron concentration was $n = 5 \times 10^{16}$ cm^{-3}. As can be seen, the electron concentration in the $InAs_{1-x}Sb_x$ solid solution decreases with an increase in the content of Sb atoms.

In Fig. 2, we show the magnetic-field dependence of the resistivity in the $InAs_{0.57}Sb_{0.43}$ samples. As can be seen, the presence of a significant magnetoresistance is observed: when the magnetic field is $B = 7$ T, the resistivity increases almost 13 times; i.e., the relative change is $\Delta\rho/\rho \approx 12$. It indicates to a high mobility of charge carriers (electrons). In addition, the beats characteristic for the Shubnikov–de-Haas oscillations are observed in the field dependence of the magnetoresistance.

The period of oscillations singled out by Fourier analysis of the field dependence of the magnetoresistance in a reverse magnetic field of intensity H turned out to be approximately equal to $P(1/H) = 2.25 \times 10^{-5}$ Oe^{-1}.

As is well known, it is possible to estimate the charge-carrier concentration n from the period P of oscillations of the magnetoresistance. In the general case, for a closed Fermi surface of arbitrary shape, the oscillation period is determined by the expression [3]

$$P\left(\frac{1}{H}\right) = \frac{2\pi e}{\hbar c S_F}. \tag{2}$$

Here, S_F is the extremal area of a cross section of the Fermi surface $E(\mathbf{k}) = \mu_F$ by a plane perpendicular to the direction of the magnetic field. For compounds such as InSb, the charge-carrier concentration is determined from the relation

$$n = \frac{1}{3\pi^2}\left(\frac{2e}{c\hbar P(1/h)}\right)^{3/2}. \tag{3}$$

Calculations according to Eq. (3) give a value of $n \approx 5.7 \times 10^{16}$ cm^{-3}.

Thus, the charge-carrier concentration determined from the Shubnikov–de-Haas oscillations agrees well with the concentration calculated from the Hall-effect measurements.

3. OPTICAL INVESTIGATIONS

To determine the optical parameters of heteroepitaxial $InAs_{1-x}Sb_x$ structures, we carried out spectral investigations using the ellipsometry method, which is a highly sensitive and accurate optical method for studying the surfaces and interfaces of various media. This method is based on studying the change in the polarization state of reflected light after its interaction with the surface of interfaces of these media. The measurements were performed using an M-2000 DI optical-range ellipsometer (J.A. Woollam Co, Inc.). The spectral dependence of the ellipsometric parameters Δ and Ψ was taken in the photon energy range of 1–6 eV with a step of 50 meV at incidence angles of 50°, 55°, and 60°.

The basic equation for ellipsometry, which relates the ellipsometric parameters Δ, Ψ, and the complex values of the Fresnel reflection coefficients r_p and r_s for the p and s components of elliptically polarized light, is written in the form [4]

$$\tan(\Psi)\exp(i\Delta) = \frac{r_p}{r_s}. \tag{4}$$

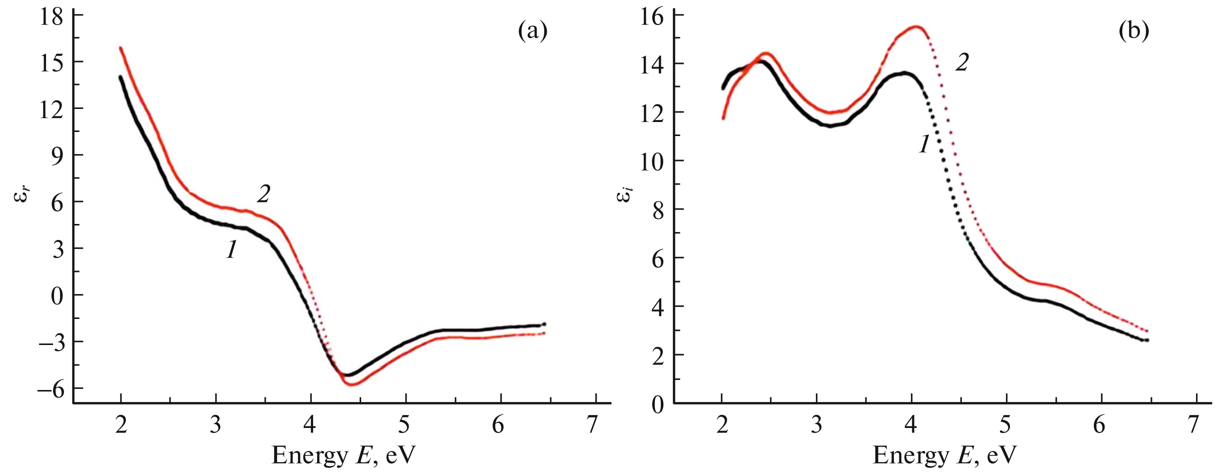

Fig. 3. Spectral dependences of (*a*) the real part ε_r and (*b*) imaginary part ε_i of the dielectric function for (*1*) $InAs_{0.57}Sb_{0.43}$ and (*2*) $InAs_{0.62}Sb_{0.38}$ heteroepitaxial structures.

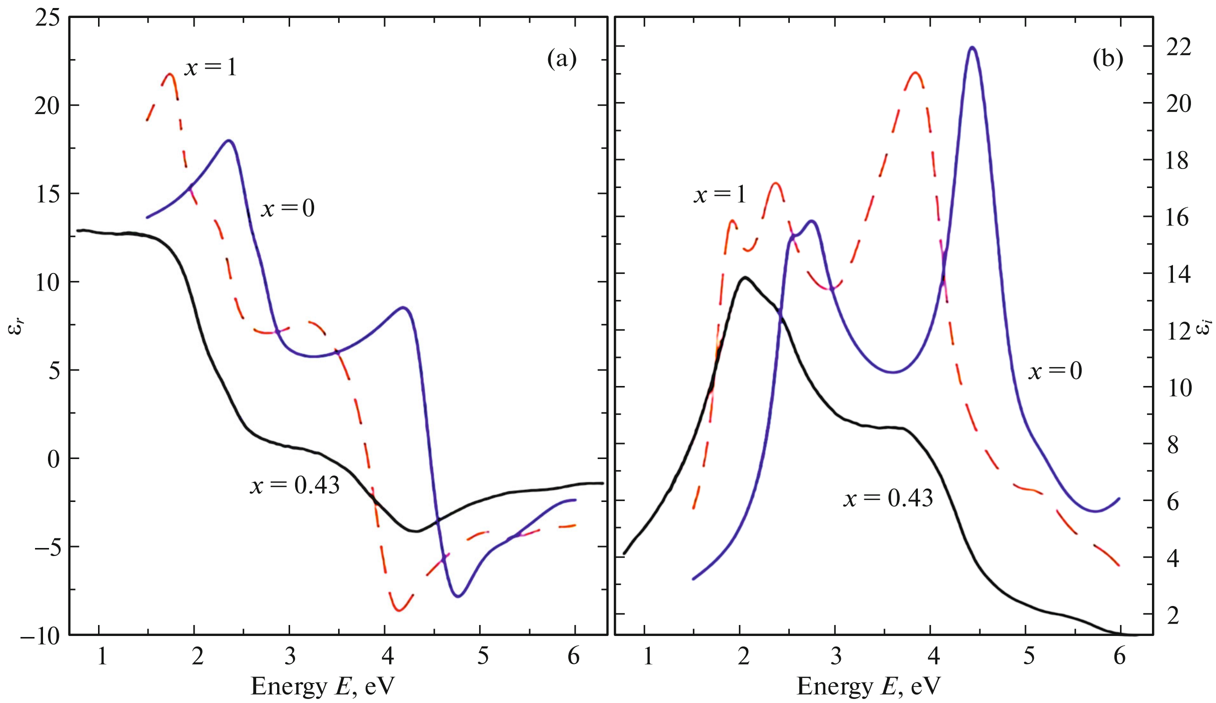

Fig. 4. Spectral dependences of the (a) real and (b) imaginary parts of the dielectric function for $InAs_{0.57}Sb_{0.43}$ ($x = 0.43$), InAs ($x = 0$), InSb ($x = 1$) heteroepitaxial structures.

The choice of an adequate optical model, which correctly describes the reflective properties of the sample under investigation is one of the important steps in ellipsometric studies. The penetration depth of optical radiation can be estimated from the relation $\lambda/2\pi k$, where k is the extinction coefficient. For visible-range optical radiation, this depth amounts to ~100 nm when analyzing the InAsSb system taking into account data on the extinction coefficient for InAs and InSb [5]. In our case, the thickness of the upper working epitaxial layer in the structures under investigation is ~400 nm [1]. This fact suggests that we obtain information in the case of ellipsometric studies only from the upper layer of the multilayer coating under investigation.

In Fig. 3, we show the real ε_r and imaginary ε_i parts of the dielectric function for $InAs_{0.57}Sb_{0.43}$ (curves *1*) and $InAs_{0.62}Sb_{0.38}$ (curves *2*). The similar nature of the

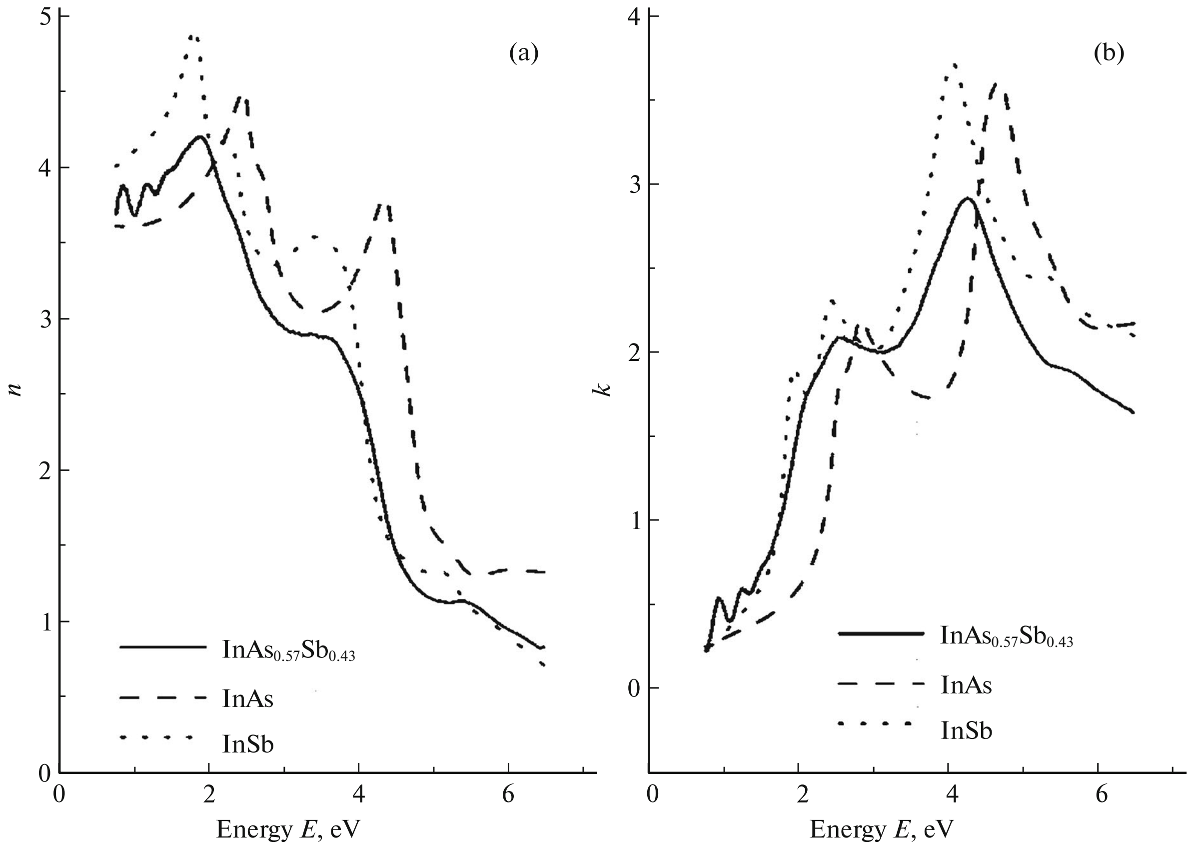

Fig. 5. Spectral dependences of the refractive index $n(E)$ and the extinction coefficient $k(E)$ for the $InAs_{0.57}Sb_{0.43}$ heteroepitaxial structure and the InAs and InSb single crystals [5].

dependences, which is not surprising for compounds with such a similar structure and similar compositions, should be noted.

For comparison, we show in Fig. 4 the real ε_r and imaginary ε_i parts of the dielectric function for the $InAs_{1-x}Sb_x$ heteroepitaxial structure ($x = 0.43$) studied by us and the InAs ($x = 0$) and InSb ($x = 1$) parent compositions for different photon energies from [5]. There is a good correlation of the features in the dependences $\varepsilon_r(E)$ and $\varepsilon_i(E)$. To calculate the refractive index n and the extinction coefficient k, we used the formulas

$$n = \sqrt{\frac{\varepsilon_r + \sqrt{\varepsilon_r^2 + \varepsilon_i^2}}{2}}, \quad (5)$$

$$k = \frac{\varepsilon_i}{\sqrt{2(\varepsilon_r + \sqrt{\varepsilon_r^2 + \varepsilon_i^2})}}. \quad (6)$$

The calculated dependences $n(E)$ and $k(E)$ for the $InAs_{0.57}Sb_{0.43}$ heteroepitaxial structure are shown in Fig. 5. The same figure shows the dependences $n(E)$ and $k(E)$ for InAs and InSb single crystals [5].

4. CONCLUSIONS

The activation energy calculated from the activation dependence of the resistivity on temperature for the $InAs_{0.57}Sb_{0.43}$ heteroepitaxial structure turned out to be 120 meV, which agrees with the band-gap data from the photoluminescence investigations of these compounds.

From Hall-effect measurements, the electron nature of the conductivity with the electron concentration $n = 6 \times 10^{16}$ cm^{-3} (for $InAs_{0.62}Sb_{0.38}$) and $n = 5 \times 10^{16}$ cm^{-3} (for $InAs_{0.57}Sb_{0.43}$) is revealed. As can be seen, the electron concentration in the $InAs_{1-x}Sb_x$ solid solution decreases with an increase in the content of Sb atoms.

Investigations of the magnetoresistance revealed its large positive magnitude in the $InAs_{1-x}Sb_x$ ($x = 0.43$ and 0.38) heteroepitaxial structures: when the magnetic field is $B = 7$ T, the resistivity increases almost 13 times; i.e., $\Delta\rho/\rho = 12$. It indicates the high mobility of charge carriers (electrons). In addition, beats characteristic of Shubnikov–de-Haas oscillations are observed in the field dependence of the magnetoresistance.

The Fourier analysis of the magnetoresistance oscillations is performed. The charge-carrier concentration estimated from the period of oscillations of the magnetoresistance turned out to be $n \approx 5.7 \times 10^{16}$ cm^{-3}, which agrees satisfactorily with the data on the Hall-effect measurement.

The values of the real ε_r and imaginary ε_i parts of the dielectric function of $InAs_{0.57}Sb_{0.43}$ and $InAs_{0.62}Sb_{0.38}$ were obtained from the spectral ellipsometric measurements in the photon energy range of 1–6 eV. The dispersion dependences of the refractive index $n(E)$ and the extinction coefficient $k(E)$ are calculated and presented.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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