Conference materials
UDC 538.958
DOI: https://doi.org/10.18721/JPM.163.108

Temperature dependence of the energy spectrum of metamorphic InSb/In(Ga,Al)As/GaAs heterostructures studied using FTIR photoreflectance spectroscopy

I.V. Chumanov [1] ✉, D.D. Firsov [1], V.A. Solov'ev [2],
M.Yu. Chernov [2], O.S. Komkov [1]

[1] St. Petersburg Electrotechnical University "LETI", St. Petersburg, Russia;
[2] Ioffe Institute, St. Petersburg, Russia
✉ chumanov2000@yandex.ru

Abstract. The paper presents the results of studies of InSb/In(Ga,Al)As/GaAs heterostructures using the photoreflectance method. Based on the results of the work, the temperature dependences of the observed transition energies were obtained, the values of the miniband width and spin-orbit splitting were determined.

Keywords: heterostructures, superlattices, quantum wells, photoreflectance method, semiconductors, FTIR spectroscopy

Funding: The work at SPbGETU "LETI" was supported by the Russian Science Foundation (grant No. 22-29-20141) and the St. Petersburg Science Foundation (grant under agreement No. 18/2022 dated April 14, 2022).

Citation: Chumanov I.V., Firsov D.D., Solov'ev V.A., Chernov M.Yu., Komkov O.S., Temperature dependence of the energy spectrum of metamorphic InSb/In(Ga,Al)As/GaAs heterostructures studied using FTIR photoreflectance spectroscopy, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.1) (2023) 47–52. DOI: https://doi.org/10.18721/JPM.163.108

Материалы конференции
УДК 538.958
DOI: https://doi.org/10.18721/JPM.163.108

Исследование температурной зависимости энергетического спектра метаморфных гетероструктур InSb/In(Ga,Al)As/GaAs с помощью метода инфракрасной Фурье-спектроскопии фотоотражения

И.В. Чуманов [1] ✉, Д.Д. Фирсов [1], В.А. Соловьёв [2],
М.Ю. Чернов [2], О.С. Комков [1]

[1] Санкт-Петербургский государственный электротехнический университет «ЛЭТИ» им. В. И. Ульянова (Ленина), Санкт-Петербург, Россия;
[2] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия
✉ chumanov2000@yandex.ru

Аннотация. В работе представлены результаты исследований энергетического спектра гетероструктур InSb/In(Ga,Al)As/GaAs при помощи метода фотоотражения. В результате работы были исследованы зависимости энергий переходов от температуры, определены значения ширины минизоны и спин-орбитального расщепления.

Ключевые слова: гетероструктуры, сверхрешетки, квантовые ямы, метод фотоотражения, полупроводники, Фурье-спектроскопия, оптика, эпитаксия

Финансирование: Работа в СПбГЭТУ «ЛЭТИ» выполнена при поддержке Российского научного фонда (грант № 22-29-20141) и Санкт-Петербургского научного фонда (грант по договору № 18/2022 от 14 апреля 2022 г.).

Ссылка при цитировании: Чуманов И.В., Фирсов Д.Д., Соловьёв В.А., Чернов М.Ю., Комков О.С. Исследование температурной зависимости энергетического спектра метаморфных гетероструктур InSb/In(Ga,Al)As/GaAs с помощью метода инфракрасной фурье-спектроскопии фотоотражения // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.1. С. 47—52. DOI: https://doi.org/10.18721/JPM.163.108

Introduction

Optoelectronic devices operating in the mid-infrared (IR) range with a wavelength of 3 to 5 micrometers have great potential in various fields of application, including gas analysis, optical wireless communication systems, and chemical process control [1]. InSb/In(Ga,Al)As/GaAs based heterostructures, which include a metamorphic buffer layer, are a promising basis for creating such devices. Important features of the structures under study are the presence of a submonolayer type II InSb insertion inside a type I InAs/InGaAs quantum well. This approach ensures effective confinement of charge carriers and an overlap of electron and hole wave functions [2]. In addition, owing to the use of InAlAs metamorphic buffer layers the studied heterostructures are grown on GaAs substrates, which are more available and cheaper than alternative substrate materials [3]. Another important feature of the structures under study is the presence of superlattice (SL) regions at the edges of the double quantum well, which play a key role in the formation of the waveguide layer and the compensation of mechanical stresses in the structure [4].

Materials and Methods

In this work, Fourier-transform infrared photoreflectance (FTIR PR) [5] spectroscopy was used to study the temperature dependence of the energy spectrum of InSb/InAs/In(Ga,Al)As/GaAs metamorphic heterostructures. The experimental setup contains a Vertex 80 FTIR spectrometer (equipped with CaF_2 and KBr beamsplitters and a liquid nitrogen-cooled InSb photodetector), an SR-830 lock-in amplifier, diode lasers with wavelengths of 405 nm and 809 nm, the radiation from which is mechanically modulated at a frequency of 2.5 kHz. The samples were placed in an optical cryostat, which can be cooled down to liquid nitrogen temperature.

The measured photoreflectance interferograms were processed in several stages: first, the algorithm for transforming into a spectrum was used, taking into account the specialized phase correction algorithm [6]. The resulting PR spectrum is normalized to the reflection spectrum, and then prepared for analysis by obtaining the “modulus of the PR spectrum” using the technique from [7]. Compared to the original PR spectrum, which typically exhibits a third-derivative differential lineshape [8], the transformed spectrum is positive, does not depend on the phase factor, and has a simple single-peak pseudo-Lorentzian form.

The samples studied in this work were grown by molecular beam epitaxy (MBE) on semi-insulating GaAs (001) substrates using a RIBER 32P setup [3]. Figure 1 shows the sketch of the band gap profile of the structures, which include a convex-graded $In_xAl_{1-x}As$ metamorphic buffer layer (MBL), an $In_{0.75}Al_{0.25}As$ virtual substrate, a 10 nm-$In_{0.82}Ga_{0.18}As$/2 nm-$In_{0.75}Al_{0.25}As$ superlattice (SL) waveguide containing an active region comprised of a type II InSb insertion within an InAs/InGaAs type I quantum well.

Samples A1, A2, and A3 differ from each other in the number of $In_{0.82}Ga_{0.18}As/In_{0.75}Al_{0.25}As$ SL periods, while the nominal thickness of the InSb insertion did not change and amounted to 1 monolayer (ML). Samples A2 and A3 used SLs with a total thickness of 310 nm, while sample A1 used a 58 nm SL. The superlattice design was chosen to achieve an average indium content of 81 mol. %, since the InAlAs layer of this composition is completely unstrained, given that the content of indium at the end of the InAlAs MBL is 87 mol. % [3]. In addition, such an SL is

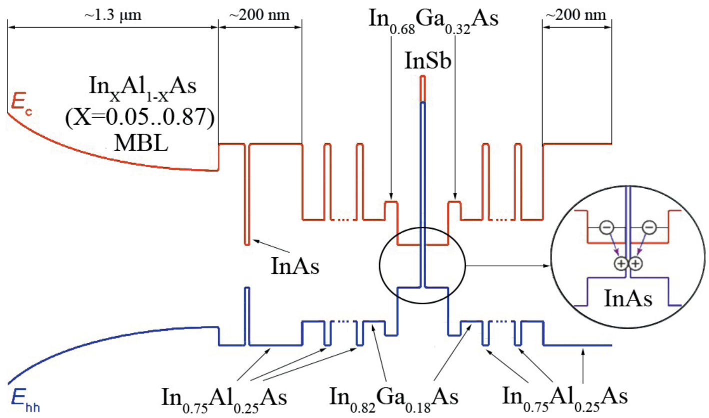

Fig. 1. Band diagram of the structures under study [3]

stress-balanced, since compressive stresses arising in the $In_{0.82}Ga_{0.18}As$ layers are compensated by tensile stresses induced by the $In_{0.75}Al_{0.25}As$ layers.

Another feature of sample A2 is the presence of a 5 nm thick GaAs insert in the metamorphic buffer (at the alloy composition of $In_{0.37}Al_{0.63}As$), which is used to reduce mechanical stresses in subsequent layers. Samples A1 and A2 also have additional $In_{0.82}Ga_{0.18}As$ barriers, which provide stronger confinement of charge carriers in the active region and reduce the possibility of carrier overflow.

Table

Distinctive features of the studied samples

Sample\structure number	A1	A2	A3
Superlattice thickness	58 nm	310 nm	
$In_xGa_{1-x}As$ barriers	$x = 0.68$, 3 nm		–
InAs QW	5 nm		
InSb insertion	1 monolayer		
Virtual substrate	$In_{0.75}Al_{0.25}As$ (InAs insert 1 nm)		
$In_{0.05..0.87}AL_{1-(0.05..0.87)}As$ MBL	–	GaAs 5 nm (insert)	–

Results and Discussion

The mid-IR photoreflectance spectra of the InSb/InAs/In(Ga,Al)As/GaAs structures exhibit a number of features corresponding to transitions between electron and hole states in the InSb/InAs/InGaAs double quantum well, which have been studied in detail in our previous work [3]. Therefore, in the current work we focus on the near-infrared range, where the studied structures exhibit signals from the $In_{0.75}Al_{0.25}As/In_{0.82}Ga_{0.18}As$ superlattice waveguide. Fig. 2, *a* shows the measured near-IR room temperature PR spectrum (“ΔR/R”, red dashed line) for one of the studied structures (sample A1), as well as its transformation using the technique from [7] (“ΔR/R Modulus”, blue solid line). The transformed PR spectrum exhibits two intensive peaks at 0.56 eV and 0.597 eV corresponding to transitions involving the edges of the miniband of the superlattice and the level of heavy holes (MB (edges) – hh_5) [3]. In addition, a higher-energy peak is present at 1.023 eV, which has not been described in such structures before. A peak at a similar energy was observed in [2] from a bulk $In_{0.75}Ga_{0.25}As$ waveguide layer, where it was attributed to the $E_0+\Delta_{SO}$ spin-orbit spit hole band. Therefore, it can be concluded that the 1.023 eV peak corresponds to the transition from the electron miniband to the spin-orbit split hole band in the $In_{0.75}Al_{0.25}As/In_{0.82}Ga_{0.18}As$ superlattice, which is observed for the first time for such structures. It should be noted that at room temperature this signal is not divided into two

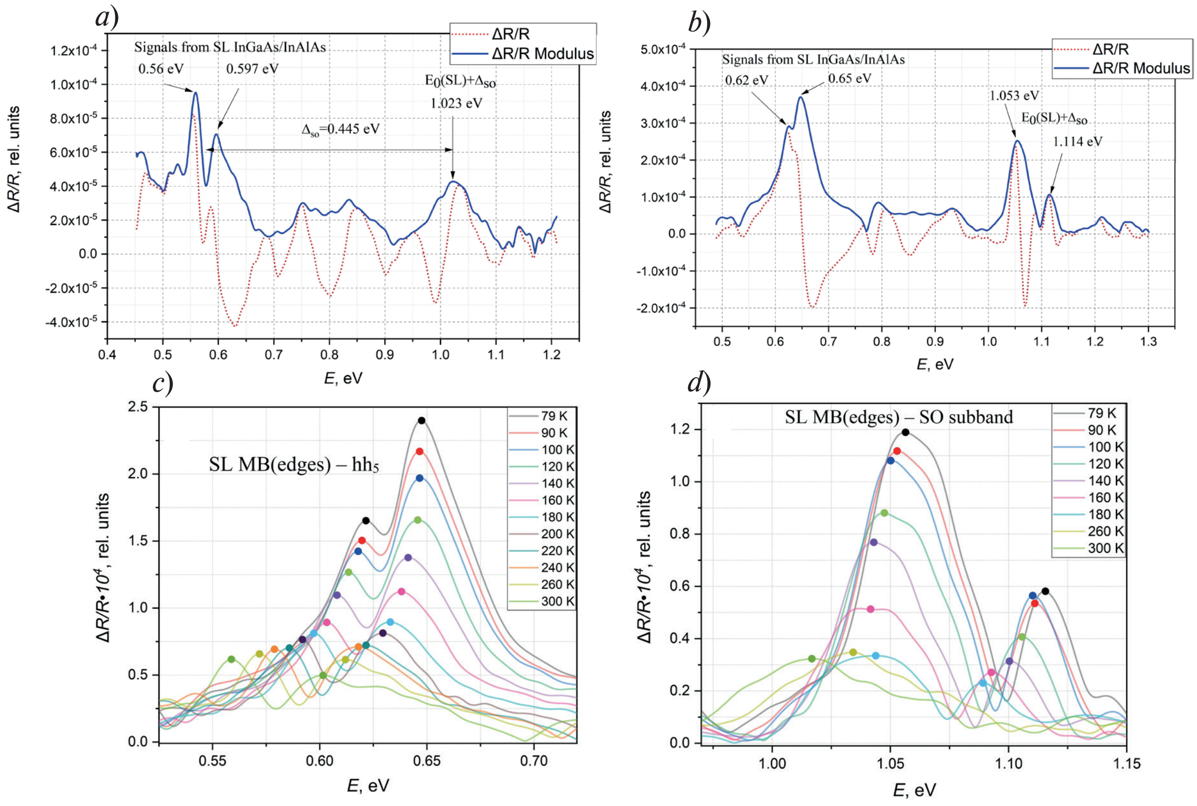

Fig. 2. Spectra of sample A1 at a temperature of 300 K (*a*), 79 K (*b*) and in the temperature range 79–300 K (*c*) and (*d*). Spectrum (*c*) shows transitions involving miniband edges and the heavy hole level; (*d*) shows transitions involving a spin-split subband; the dots mark the maxima. For (*a*) and (*b*): red line - normalized photoreflectance spectrum, blue line and the spectra in (*c*) and (*d*) - transformed spectrum according to the description method in [7]

separate peaks, which is likely due to broadening of the spectrum. The estimated values of the spin–orbit splitting turned out to be 0.445 eV for sample A1, 0.433 eV for A2, and 0.441 eV for A3, respectively, which are close to the 0.465 eV value obtained in [2] for bulk $In_{0.75}Ga_{0.25}As$.

When the same sample A1 was cooled to liquid nitrogen temperature, this broad peak splits into two separate peaks (see Fig. 2, *b*) with transition energies of 1.053 eV and 1.114 eV. This splitting confirms the relation of the higher-energy PR peak to the miniband of the $In_{0.75}Al_{0.25}As/In_{0.82}Ga_{0.18}As$ superlattice. At the same time the main SL peaks, which correspond to electron transitions from the miniband edges to the level of heavy holes hh5, became noticeably closer to each other. This may indicate a change in the width of the superlattice miniband.

To conduct a deeper analysis of the detected signals, PR measurements were performed over a broad temperature range from 79 K to 300 K. The corresponding transformed PR spectra in the region of the main and spin-orbit split SL transitions are shown in (Fig. 2, *c*, *d*). It can be noted that for sample A1 at low temperatures the signal from the spin-orbit split transitions exhibits two separate peaks, each of which can be attributed to the participation of one of the miniband edges.

The position of the peaks can be more accurately estimated from the dependences of the change in the energy value on temperature, which is shown in Fig. 3 (where the transitions with the participation of the upper edge of the miniband are marked in red, and the transitions with the lower edge are marked in blue). The experimental data were approximated by the Varshni equation.

The right chart in Fig. 3, *b* shows, in addition to the experimental temperature dependences, the calculated temperature dependences of the band gap for bulk $In_{0.75}Al_{0.25}As$ and $In_{0.82}Ga_{0.18}As$ crystals. Thus, it becomes possible to follow the change in the position of the miniband in the band diagram depending on the temperature. For samples A2 and A3, the temperature dependences are similar (see Fig. 3, *c*, *d*). Comparing the dependences in Fig. 3, *a*, *c*, and *d*, it can be seen that for samples A2 and A3, with increasing temperature, the miniband width changes very slightly in

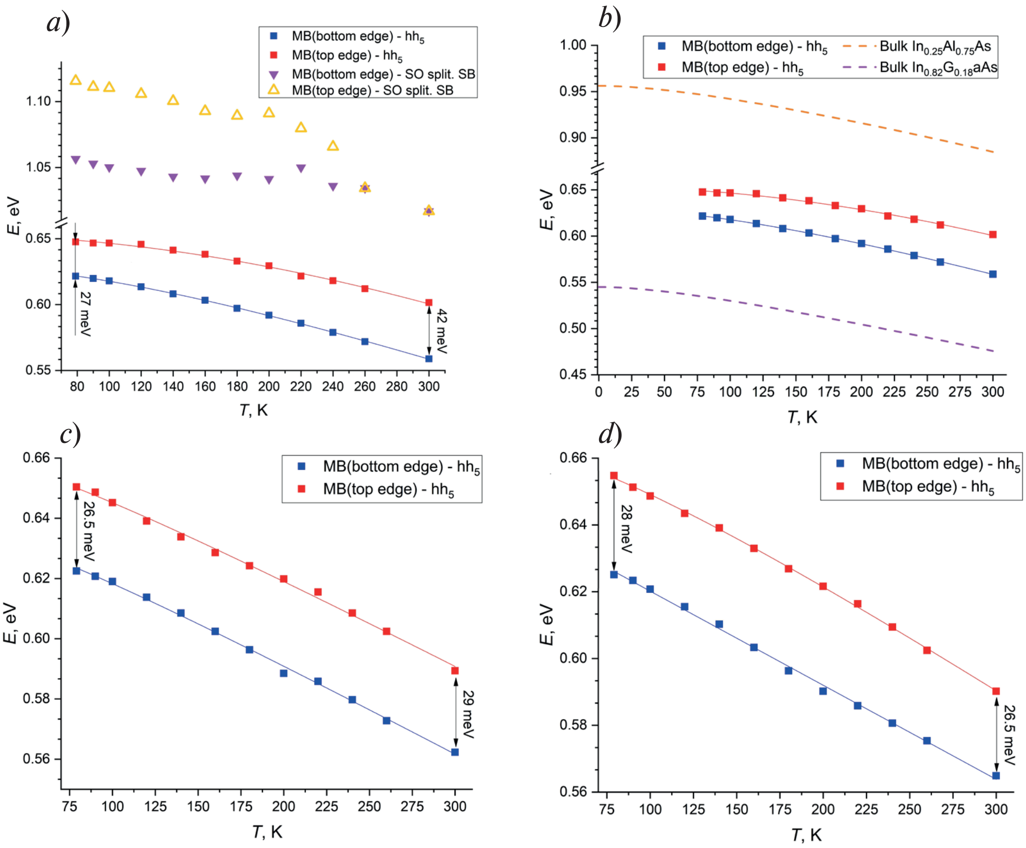

Fig. 3. Temperature dependences of the transition energy for samples A1 (*a*, *b*), A2 (*c*) and A3 (*d*) (square - transitions involving miniband edges and the level of heavy holes (hh_5); triangle - transitions involving the spin-split subband; dashed line - theoretical calculation of the temperature dependence of the band gap for bulk materials, from of which the SL consists)

comparison with the first sample. Thus, for sample A2, the value of this quantity was 26.5 meV at 79 K and 29 meV at 300 K, for sample A3 it was 28 meV at 79 K and 26.5 meV at 300 K. At the same time, for the A1 sample the calculated values of the width of the electron miniband in the superlattice were 27 meV at T = 79 K and 42 meV at T = 300 K, which indicates a broadening of the miniband. It should also be noted that determination of the miniband width value from the transitions to the spin-split subband in the same sample A1 results in a significantly higher value of 59 meV at 79 K. The reason for such difference is not clear at the moment, and will be explored during further studies.

Conclusion

As a result of the studies performed, transitions involving an electron miniband and a spin-split subband were discovered in the waveguide region of the samples, consisting of superlattices, and the values of the spin-orbit splitting were also calculated for them. From the temperature analysis, the widths of the miniband at temperatures of 79 and 300 K were found. The results obtained make it possible to supplement the characteristics of the structures under study.

Acknowledgments

The authors would like to deeply thank Prof. S.V. Ivanov for the original concept of the studied metamorphic heterostructures, and his prolonged guidance of their research.

REFERENCES

1. **Firsov D.D., Chernov M.Yu., Solov'ev V.A., Komkov O.S.,** Characterization of In (Ga, Al) As/GaAs metamorphic heterostructures for mid-IR emitters by FTIR photoreflectance spectroscopy. Journal of Physics: Conference Series (Vol. 2086 (1) (2021) 012140). IOP Publ.

2. **Ivanov S.V., Chernov M.Yu., Solov'ev V.A., Brunkov P.N., Firsov D.D., Komkov O.S.,** Metamorphic InAs (Sb)/InGaAs/InAlAs nanoheterostructures grown on GaAs for efficient mid-IR emitters. Progress in Crystal Growth and Characterization of Materials, 65 (1) (2019) 20–35.

3. **Chernov M.Yu., Solov'ev V.A., Komkov O.S., Firsov D.D., Andreev A.D., Sitnikova A.A., Ivanov S.V.,** Effect of design and stress relaxation on structural, electronic, and luminescence properties of metamorphic InAs(Sb)/In(Ga,Al)As/GaAs mid-IR emitters with a superlattice waveguide. Journal of Applied Physics, 127(12), 2020, 125706.

4. **Solov'ev V.A., Chernov M.Yu., Komkov O.S., Firsov D.D., Sitnikova A.A., Ivanov S.V.,** Effect of Strongly Mismatched GaAs and InAs Inserts in a InAlAs Buffer Layer on the Structural and Optical Properties of Metamorphic InAs (Sb)/InGaAs/InAlAs/GaAs Quantum-Confined Heterostructures. JETP Letters, 109 (2019), 377–381.

5. **Hosea T.J.C., Merrick M., Murdin B.N.,** A new Fourier transform photo-modulation spectroscopic technique for narrow band-gap materials in the mid-to far-infra-red. physica status solidi (*a*), 202 (7) (2005) 1233–1243.

6. **Firsov D.D., Komkov O.S.,** Photomodulation Fourier transform infrared spectroscopy of semiconductor structures: features of phase correction and application of method. Technical Physics Letters, 39 (2013) 1071–1073.

7. **Hosea T.J.C.,** Estimating Critical-Point Parameters of Modulated Reflectance Spectra. physica status solidi (b), 189 (2) (1995) 531–542.

8. **Aspnes D.E.,** Third-derivative modulation spectroscopy with low-field electroreflectance. Surface science, 37, (1973) 418–442.

THE AUTHORS

CHUMANOV Ivan V.
chumanov2000@yandex.ru
ORCID: 0009-0009-2564-6100

CHERNOV Mikhail Yu.
chernov@beam.ioffe.ru
ORCID: 0000-0003-0904-2752

FIRSOV Dmitrii D.
d.d.firsov@gmail.com
ORCID: 0000-0001-7608-9580

KOMKOV Oleg S.
oleg_sergeevich@mail.ru
ORCID: 0000-0002-8999-1175

SOLOV'EV Viktor A.
vasol@beam.ioffe.ru

Received 05.07.2023. Approved after reviewing 16.08.2023. Accepted 16.08.2023.