FTIR photoreflectance of narrow-gap heterostructures based on $\text{Al}_x \text{In}_{1-x} \text{Sb}$ alloys

To cite this article: D D Firsov et al 2017 J. Phys.: Conf. Ser. 917 062025

View the article online for updates and enhancements.
FTIR photoreflectance of narrow-gap heterostructures based on Al$_x$In$_{1-x}$Sb alloys

D D Firsov$^1$, O S Komkov$^{**1}$, V A Solov'ev$^2$, A N Semenov$^2$, and S V Ivanov$^2$

$^1$Micro- and Nanoelectronics department, St. Petersburg Electrotechnical University “LETI”, Professora Popova 5, St. Petersburg 197376, Russia
$^2$Ioffe Institute, Politekhnicheskaya 26, St. Petersburg 194021, Russia

Abstract. Photoreflectance (PR) spectra of Al$_x$In$_{1-x}$Sb-based heterostructures have been obtained by using a novel photomodulation Fourier-transform infrared (FTIR) spectroscopy method. The studied samples - bulk Al$_x$In$_{1-x}$Sb epilayers and InSb/Al$_x$In$_{1-x}$Sb heterostructures - were grown by molecular beam epitaxy on semi-insulating GaAs substrates via AlSb buffer layers. The critical-point energies $E_0$ and $E_0 + \Delta_0$ of Al$_x$In$_{1-x}$Sb alloys of various direct-gap compositions were defined from the PR spectra features. It was found that the $E_0$ values are greater than the observed Al$_x$In$_{1-x}$Sb photoluminescence peak energy, with the difference increasing with $x$. For the InSb/Al$_x$In$_{1-x}$Sb heterostructures, PR signals corresponding to Franz-Keldysh oscillations in the alloy barrier have been observed. Analysis of their period has allowed one to determine the intensity of the internal electric field in Al$_x$In$_{1-x}$Sb layers. This result enables evaluation of the surface Fermi level pinning, and elucidation of the effect of doping in such heterostructures.

1. Introduction

Narrow-gap Al$_x$In$_{1-x}$Sb alloys are the optimal barrier material for quantum well (QW) heterostructures based on InSb – a III-V semiconductor with the highest electron mobility and the largest g-factor – since their lattice parameters are close to that of InSb, and the band offsets increase rapidly with $x$. The InSb/Al$_x$In$_{1-x}$Sb QW heterostructures are promising for numerous applications, such as super high-frequency, low-voltage high-electron-mobility transistors (HEMT) with cutoff frequency above 300 GHz [1, 2], mid-infrared (IR) light-emitting diodes of the 4-5 $\mu$m range [3, 4], and even detectors of terahertz radiation [5]. The use of Al$_x$In$_{1-x}$Sb instead of InSb for IR focal plane arrays shifts their spectral range towards shorter wavelengths, and enables an increase of operating temperature from 80 K to 110 K [6, 7]. In addition, Sb-based III-V compounds are considered to be promising for silicon-based optoelectronic devices grown directly on Si substrates [8].

However, the fundamental properties of the Al$_x$In$_{1-x}$Sb alloys, as dependent on $x$, have only been briefly investigated, and the available data are quite scarce [9] and based on studies of polycrystalline samples with a high $x$ gradient. Moreover, there exist only few publications dedicated to studying the optical properties of InSb/Al$_x$In$_{1-x}$Sb heterostructures (see e.g. [10-12]).

In this work, a novel Fourier-transform infrared (FTIR) photoreflectance (PR) spectroscopy method [13] is applied to study the optical properties and band structure of epitaxial Al$_x$In$_{1-x}$Sb alloys, as well as InSb/Al$_x$In$_{1-x}$Sb heterostructures. To the best of our knowledge, the photoreflectance of Al$_x$In$_{1-x}$Sb is...
observed experimentally for the first time. The PR spectral features are analyzed in order to determine the interband transition energies, and the intensity of the electric field in the Al\textsubscript{x}In\textsubscript{1-x}Sb barriers.

2. Samples and experimental setup

The studied Al\textsubscript{x}In\textsubscript{1-x}Sb epitaxial layers and InSb/Al\textsubscript{x}In\textsubscript{1-x}Sb heterostructures were grown by molecular beam epitaxy (MBE) on lattice-mismatched semi-insulating (001) GaAs substrates via AlSb buffer layers. A RIBER 32P MBE setup was employed, and \( x \) was determined by using electron probe microanalysis and X-ray diffraction measurements [14]. Due to the large thickness of the Al\textsubscript{x}In\textsubscript{1-x}Sb epilayers (~1 µm), as determined using both an optical technique described in [15] and scanning electron microscopy measurements, the elastic strain is assumed to be fully relaxed [16].

In the InSb/Al\textsubscript{x}In\textsubscript{1-x}Sb heterostructures, a 30 nm-thick InSb QW was grown at 50 nm beneath the surface of thick (1.6 – 3.3 µm) Al\textsubscript{x}In\textsubscript{1-x}Sb epitaxial layers delta-doped with Te above the QW. A \{3nm-InSb/3nm-Al\textsubscript{x}In\textsubscript{1-x}Sb\}\texttimes12 superlattice was incorporated in the Al\textsubscript{x}In\textsubscript{1-x}Sb buffer to suppress propagation of defects to the surface layer.

The optical setup is based upon a VERTEX 80 FTIR spectrometer equipped for measurements in the 0.9 – 16 µm range. During PR measurements, the samples were placed into a liquid nitrogen cryostat and excited by a 809 nm laser diode (\( P_{\text{in}} \) up to 300 mW), which was electrically modulated at 2.5 kHz. The PR component of the signal was amplified by using a SR-830 lock-in amplifier tuned to the modulation frequency, digitized by internal ADC of the spectrometer, and processed by using an algorithm described in Ref. [17]. Photoluminescence (PL) spectra of the studied samples were measured by using the same spectrometer and excitation laser, and a CCS-150 closed-cycle helium cryostat.

3. Results and discussion

The photoreflectance spectra \( \Delta R/R \) (\( T = 100 \text{ K} \)) of Al\textsubscript{x}In\textsubscript{1-x}Sb epitaxial layers with different \( x \), which are supposed to be the only available in literature to date, are presented in Figure 1, along with their low-temperature (\( T = 10 \text{ K} \)) PL. The PL spectra at \( T = 100 \text{ K} \) are not presented here since most of the samples did not show PL signals from Al\textsubscript{x}In\textsubscript{1-x}Sb layers at that temperature.

![Figure 1](image-url)

**Figure 1.** Photoreflectance (solid lines) and photoluminescence (dashed lines) spectra of Al\textsubscript{x}In\textsubscript{1-x}Sb alloy layers of various composition \( x \).
The PR spectra exhibit characteristic derivative-like features, attributed to the $\Gamma_6 - \Gamma_8$ interband critical point $E_0$ of the band structure (corresponding to the direct band gap of Al$_x$In$_{1-x}$Sb). In modulation spectroscopy, such kind of lineshape is typical for so-called low-field regime [18] when a characteristic electro-optic energy $\hbar\Omega$ is less than or equal to a broadening parameter. In this case $\hbar\Omega \sim F^{2/3}$, where $F$ is a surface electric field, and the broadening parameter is defined by structural quality of the samples. The critical point energies $E_0$ (marked by arrows on Figure 1) were determined from the PR spectra using a technique employing a Kramers-Kronig transformation, described in Ref. [19]. The obtained $E_0$ values match reasonably well to the PL peak position in case of the InSb film, and are noticeably higher than the observed PL peak energies $E_{\text{max}}^{\text{PL}}$ in the case of the Al$_x$In$_{1-x}$Sb layers, as illustrated in Figure 2a. This difference tends to increase with $x$, and might be related to the disordering of the Al$_x$In$_{1-x}$Sb alloy or radiative transitions involving impurity or defect levels within the band gap.

![Figure 2a](image1.png)  ![Figure 2b](image2.png)

**Figure 2a.** Difference between $E_0$ from PR and PL peak energy of Al$_x$In$_{1-x}$Sb as a function of $x$. A linear trend line is added as a guide for eye.

**Figure 2b.** Full width at half maximum (FWHM) of the Al$_x$In$_{1-x}$Sb alloy PL peak.

The correlation between the observed energy difference and the Al$_x$In$_{1-x}$Sb PL linewidth (Figure 2b) implies that the PL peak energy might be decreased relatively to the interband optical transition energy $E_0$ due to the contribution of a band tail in Al$_x$In$_{1-x}$Sb to the PL lineshape.

The PR spectra of InSb/Al$_x$In$_{1-x}$Sb heterostructures have exhibited a variety of spectral features, comprising of intensive signals from Al$_x$In$_{1-x}$Sb barriers not only at $E_0$ critical energy, but also at $E_0 + \Delta_0$ transition from the spin-orbit split valence band (shown in Figure 3).
Figure 3. PR of Al$_x$In$_{1-x}$Sb alloy heterostructures near the spin-orbit split band transition.

The energies of the $E_0+\Delta_0$ transitions were also determined from the PR spectra by using the above-mentioned Kramers-Kronig transformation technique [19]. The resulting $E_0$ and $E_0+\Delta_0$ values for the Al$_x$In$_{1-x}$Sb layers are plotted as a function of alloy composition in Figure 4.

Figure 4. Dependence of the interband critical point energies of the Al$_x$In$_{1-x}$Sb alloy epilayers on the composition $x$.

The $E_0(x)$ dependence can be described by a conventional quadratic relation with a rather small bowing parameter, in agreement with our previous work [20]. The spin-orbit splitting energy values (obtained as $\Delta_0 = (E_0+\Delta_0) - E_0$) are in the 0.68 - 0.78 eV range, which correlates well with the available data for InSb and AlSb [9].
The samples with InSb/Al$_{1-x}$Sb heterostructures have exhibited a periodic oscillating structure in the PR spectra above the $E_0$ energy, caused by Franz-Keldysh oscillations (FKOs) in Al$_{1-x}$Sb. Example of such PR spectrum is shown in Figure 5. This lineshape differs from the derivative-like features observed above, and corresponds to intermediate-field regime [18] when $\hbar \Omega$ is greater than or approximately equal to the broadening parameter. Electric field $F$ (and hence $\hbar \Omega$) in the InSb/Al$_{1-x}$Sb heterostructure samples is expected to be greater than in the Al$_{1-x}$In$_{1-x}$Sb alloys (because of additional Te doping). At the same time the broadening should be smaller, since the density of defects is reduced owing to the presence of the superlattice.

Compared to the PL of similar structures [11], PR measurements provide additional information about the barrier layers. In case of heterostructures with QWs, the PR spectra also exhibit signals from exciton transitions in the wells, which will be reported elsewhere.

![Figure 5](image.png)

*Figure 5.* Franz-Keldysh oscillations in PR spectrum of a typical InSb/Al$_{1-x}$Sb epitaxial heterostructure. The surface field intensity determined from FKO equals to 24kV/cm.

The lineshape of the FKO can be described with a known relation (see e.g. [21]). The period of the oscillations is increased with the intensity of internal electric field $F$. The result of determining the field intensity $F$ in Al$_{1-x}$Sb from the PR spectrum using the approach described in Ref. [22] is presented in Figure 5 caption. The intensity of the surface electric field is governed by the concentration of free carriers in the semiconductor layer (and hence, doping), as well as by the surface states (which define the Fermi level pinning).

Observation of Franz-Keldysh oscillations enables one to extract the value of surface Fermi level pinning in Al$_{1-x}$Sb, provided that the carrier concentration in the studied samples would be known from independent measurements (e.g. Hall effect). And vice versa, the known surface pinning value $E_F$ would enable one to obtain the free carrier concentration from the filed intensity derived from the FKO period in the PR spectra. Therefore, a contactless technique of determining the free carrier concentration in Al$_{1-x}$Sb epilayers can be developed, which is the subject of future research.

In conclusion, it was demonstrated that the PR spectra of Al$_{1-x}$Sb measured with FTIR modulation spectroscopy method provide information on the energies of critical-points corresponding to both the direct band gap ($E_0$) and the spin-orbit split valence band transition ($E_0+\Delta_0$). Compared to the observed PL peak energies $E_{\text{max,PL}}$ of the Al$_{1-x}$Sb alloy, the obtained $E_0$ values are systematically

---

5

---
higher. Observation of Franz-Keldysh oscillations in the PR spectra of InSb/Al$_x$In$_{1-x}$Sb heterostructures has allowed us to determine the intensity of the internal electric field in Al$_x$In$_{1-x}$Sb layers.

Acknowledgments
D.D. Firsov acknowledges the support of RFBR, project № 16-32-60076 mol_a_dk. O.S. Komkov acknowledges the support of Ministry of Education and Science of Russia, research project 16.1750.2017/PCh.

References
[1] Ashley T and Buckle L 2007 Electronics Letters 43 14
[2] Yi W, Kiselev A A, Thorp J, Noah R, Nguyen B M, Bui S, Rajavel R D, Hussain T, Gyure M F, Kratz P, Qian Q, Manfra M J, Pribiag V S, Kouwenhoven L P, Marcus Ch M and Sokolich M 2015 Applied Physics Letters 106 142103
[3] Nash G R and Mirza B I 2013 Applied Physics Letters 102 011127
[4] Meriggi L, Steer M J, Ding Y, Thayne I G, MacGregor C, Ironside Ch N and Sorel M 2015 Journal of Applied Physics 117 063101
[5] Gouider F, Vasilyev Yu B, Bugár M, Könemann J, Buckle P D and Nachtwei G 2010 Phys. Rev. B 81 155304
[6] Glozman A, Harush E, Jacobsohn E, Klin O, Klipstein P, Markovitz T, Nahum V, Saguy E, Olkinine-Schlesinger J, Shtrichman I, Yassen M, Yofis B and Weiss E 2006 Proc. of SPIE 6206 62060M
[7] Lyu Y, Si J, Cao X, Zhang L, Peng Z, Ding J, Yao G, Zhang X and Reobrazhenskiy V 2016 Proc. of SPIE 9819 98191K
[8] Rodriguez J B, Madismanana K, Cerutti L, Castellano A, Tournié E 2016 Journal of Crystal Growth 439 33
[9] Vurgaftman I, Meyer J R and Ram-Mohan L R 2001 Journal of Applied Physics 89 5815
[10] Litvinenko K L, Murdin B N, Allam J, Pidgeon C R, Bird M, Morris K, Branford W, Clowes S K, Cohen L F, Ashley T and Buckle L 2006 New Journal of Physics 8 49
[11] Mironova M S, Komkov O S, Firsov D D and Glinskii G F 2014 Journal of Physics: Conference Series 541 012085
[12] Chen G, Sun W and Lv Y 2017 Infrared Physics & Technology 81 262
[13] Komkov O S, Firsov D D, Lvova T V, Sedova I V, Semenov A N, Solov’ev V A, Ivanov S V 2016 Physics of the Solid State 58 2394
[14] Semenov A N, Meltser B Y, Solov’ev V A, Komissarova T A, Sitnikova A A, Kirylenko D A, Nadtochiy A M, Popova T V, Kop’ev P S and Ivanov S V 2011 Semiconductors 45 1327
[15] Komkov O S, Firsov D D, Semenov A N, Meltser B Y, Troshkov S I, Pikhtin A N and Ivanov S V 2013 Semiconductors 47 292
[16] Komkov O S, Semenov A N, Firsov D D, Meltser B Ya, Solov’ev V A, Popova T V, Pikhtin A N and Ivanov S V 2011 Semiconductors 45 1425
[17] Firsov D D and Komkov O S 2013 Technical Physics Letters 39 1071
[18] Aspnes D E 1973 Surface Science 37 418
[19] Hosea T J C 1995 Physica Status Solidi B 189 531
[20] Komkov O S, Firsov D D, Pikhtin A N, Semenov A N, Meltser B Ya, Solov’ev V A and Ivanov S V 2011 AIP Conference Proceedings 1416 184
[21] Hughes P J, Weiss B L and Hosea T J C 1995 Journal of Applied Physics 77 6472
[22] Pikhtin A N, Komkov O S and Bazarov K V 2006 Semiconductors 40 592