Characterization of In(Ga,Al)As/GaAs metamorphic heterostructures for mid-IR emitters by FTIR photoreflectance spectroscopy

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Abstract. Infrared photoreflectance (PR) spectra of In(Ga,Al)As/GaAs metamorphic heterostructures have been obtained using a novel photomodulation FTIR spectroscopy technique. An analysis of the PR spectra features allowed us to estimate the critical point energies corresponding to the direct interband transitions in various regions of the In(Ga,Al)As heterostructures, and distinguish the PR signals originating from Fabry-Perot interference. Observation of Franz-Keldysh oscillations originating from the InAlAs virtual substrate and an InGaAs waveguide layer has enabled determination of the built-in electric field intensities within the heterostructures. The obtained results open up possibilities for contactless control of free carrier concentration in In(Ga,Al)As/GaAs metamorphic heterostructures developed for growth of emitters of mid-IR spectral range.

1. Introduction

In(Ga,Al)As/GaAs metamorphic heterostructures have been recently shown to be very promising for high-efficiency semiconductor lasers and light-emitting diodes operating in the 3–5 μm mid-infrared (mid-IR) spectral range [1]. Such emitters are in demand for a variety of applications, including optical gas sensing, chemical process control, noninvasive medical tests, and free-space optical communications [2,3]. A promising approach to their creation is based on the formation of an active region comprising a type-II submonolayer InSb insertion embedded in the middle of a type-I InAs/InGaAs quantum well, which provides good confinement of carriers along with a rather strong overlap of electron and hole wave functions [1]. The key element of such structures is a convex-graded InₓAl₁₋ₓAs metamorphic buffer layer (MBL) [4], which enables fabrication of low-defect-density active region on strongly lattice mismatched but well-developed GaAs substrates.

This work is devoted to applying a novel photomodulation spectroscopy technique based on a Fourier-transform infrared (FTIR) spectrometer [5] for studying the properties of In(Ga,Al)As/GaAs metamorphic structures, which are playing the role of a “virtual substrate” for the active region of mid-IR emitters. FTIR photoreflectance spectra, obtained both at room and at low temperatures, include a number of features corresponding to direct interband transitions in the InGaAs and InAlAs layers, as well as Franz-Keldysh oscillations, the analysis of which enables contactless determination of internal electric fields within the metamorphic In(Ga,Al)As/GaAs mid-IR emitter structures.
2. Experimental setup

The studied In(Ga,Al)As metamorphic structures were grown by molecular-beam epitaxy (MBE) in a RIBER 32P setup on semi-insulating (SI) GaAs (001) substrates via a convex-graded InAl0.3As metamorphic buffer layer [4]. The composition profile of the MBL is described by a dependence \( x(z) = x_i + (x_{\max} - x_i)(z/L)^{0.5} \), where \( x_i \) and \( x_{\max} \) are the In contents at the bottom and the top of MBL, and \( L \) – its total thickness [5]. Atop the MBL an In0.70Al0.30As layer of constant composition was grown (as illustrated in the inset of Fig. 1b), which is intended as a “virtual substrate” (VS) for an active region of the mid-IR sources. Some of the studied structures also included a thick In0.75Ga0.25As layer within an In0.78Al0.22As VS (see the inset of Fig. 2), which is a prototype of a waveguide where an emitting quantum well is to be located.

The optical setup for photomodulation measurements was based upon a VERTX 80 FTIR spectrometer equipped with InSb and CdHgTe detectors, enabling spectra measurements in the 0.9 - 16 \( \mu \)m range. During the photoreflectance (PR) measurements, the samples were excited by a 405 nm or an 809 nm laser diode (\( P_{\text{las}} \) up to 100 mW), which was modulated at 3.5 kHz. The PR component of the signal was amplified by a SR-830 lock-in amplifier tuned to the frequency of modulation, then digitized by the spectrometer’s internal ADC, and processed using an algorithm described elsewhere [7]. Additionally, photoluminescence (PL) spectra of the studied samples were measured with the same spectrometer, excitation laser, and a closed-cycle helium cryostat (Janis CCS-150) as described earlier [8]

3. Results and discussion

The first part of the work was devoted to studying the properties of the basic (In,Al)As/GaAs structures, which contain a single virtual substrate layer atop a metamorphic MBL. The photoreflectance spectra A\(R/R\) of a typical heterostructure with an In0.70Al0.30As VS layer are presented in Figure 1 a,b. It can be seen that the PR spectra exhibit a number of features, which differ significantly at cryogenic and room temperature.

![Figure 1. Photoreflectance spectra of a metamorphic structure with a thick In0.70Al0.30As virtual substrate (VS) measured at room (a) and low (b) temperature. The arrow marks the interband transition energy obtained using the technique from Ref. [9]. The brackets highlight the spectral regions containing Franz-Keldysh oscillations (a), and Fabry-Perot interference (b), respectively. The inset in (b) shows the sketch of the layers within the heterostructure.](image)

The broad differential-like feature at 0.97-1.03 eV observed PR in the spectrum at 300 K (Fig. 1, a) can be attributed to the direct interband transition \( E_g \) in the virtual substrate. Indeed, the critical point energy value of 1.00 eV, determined using a modified three-point method from Ref. [9], matches precisely the expected band gap of In0.70Al0.30As (estimated according to data from [10]). The periodic oscillating structure in the same PR spectrum at higher energy (1.03-1.12 eV range) corresponds to
Franz-Keldysh oscillations (FKOs) within the In$_{0.70}$Al$_{0.30}$As layer. Analyzing the period of FKO enables determination of the intensity $F$ of the internal electric field, using a technique described in Ref. [11]. The obtained field value for the sample from Fig. 1 is $F = 21.3 \pm 0.5$ kV/cm. Considering the large thickness (1.03 µm) of the VS layer, which clearly exceeds the penetration depth of the 809 nm laser into In$_{0.70}$Al$_{0.30}$As, the observed electric field is evidently related to the near-surface region. The intensity of a surface electric field in a semiconductor layer depends on the density of the charged states at the surface (characterized by Fermi level pinning), and the concentration of free carriers within the material (see eg. [5]). Therefore, given that the Fermi level pinning value could be determined independently, the obtained results open up a possibility of determining free carrier concentration in (In,Al)As virtual substrates based on analysis of the period of FKO in their PR spectra.

The low temperature PR spectrum (Fig. 1, b) also exhibits an oscillating structure, but its period is significantly greater than that of FKO observed at 300K. Considering that the period of FKO is proportional to the field intensity (and hence to the carrier concentration, which is strongly decreased at 120K), this signal is obviously of another origin. The period of the oscillations matches that of the Fabry-Perot interference signal observed in the reflectance spectra $R$ of the (In,Al)As/GaAs structure. Analyzing the distance between the PR peaks to determine the layer thickness $d$ using a technique described in [12] with an effective refractive index of $n=3.46$ (calculated by a model from [13] at $\lambda = 1.15$ µm for an In$_{0.70}$Al$_{0.30}$As alloy) results in a value of $d = 2160$ nm, which is close to the combined thickness of the (In,A)As VS and MBL epitaxial layers. Therefore, it can be concluded that the oscillating signal observed in the PR spectra at 120 K corresponds to the photoinduced change in the refractive index (see eg. [14]), which causes the modulation of Fabry-Perot interference in the epitaxial structure.

The photoreflectance spectrum $\Delta R/R$ of a complex In(Ga,Al)As/GaAs metamorphic heterostructure with an (In,Ga)As waveguide layer is presented in Figure 2, along with the photoluminescence of the same structure.

![Figure 2](image_url)

**Figure 2.** Photoreflectance and photoluminescence spectra of a metamorphic structure with an In$_{0.75}$Ga$_{0.25}$As waveguide layer. The arrows mark the transition energies obtained using the techniques from Ref. [16] ($E_0$) and Ref. [9] ($E_0+\Delta_{SO}$). The bracket shows the spectral region containing Franz-Keldysh oscillations in InGaAs. The inset shows the sketch of the layers within the heterostructure.

It can be seen that in the 0.55-0.65 eV range, where a PL peak from the direct interband transition in In$_{0.75}$Ga$_{0.25}$As is present, the PR spectrum exhibits a signal with a number of Franz-Keldysh oscillations, evidently related to the same In$_{0.75}$Ga$_{0.25}$As layer. To the best of our knowledge, FKO have not been reported for In$_x$Ga$_{1-x}$As with $x$ above 0.53[15], which makes this result the first...
experimental observation of Franz-Keldysh oscillations for an In$_{0.75}$Ga$_{0.25}$As alloy of such a high indium composition.

The lineshape of the near-band-edge PR signal from the In$_{0.75}$Ga$_{0.25}$As waveguide exhibiting Franz-Keldysh oscillations is characteristic of the so-called intermediate-field regime (see eg. [17]). In this case the exact band gap can be determined from the FKO signal according to a model from [16], which has resulted in a value of $E_0 = 0.563$ eV. Meanwhile, an analysis of the differential signal observed in the higher-energy part of the PR spectrum using an aforementioned three-point technique [9] results in a corresponding critical point energy of 1.028 eV. This value is significantly above the band gap of bulk In$_{0.75}$Al$_{0.25}$As at 300 K (0.890 eV according to [10]). However, a 0.465 eV difference between this signal and the $E_0$ peak is rather close to the expected spin-orbit splitting value for an In-rich alloy ($\Delta_{SO} = 0.39$ eV for InAs [10]), and thus the 1.028 eV peak can likely be interpreted as a $E_0 + \Delta_{SO}$ transition in In$_{0.75}$Ga$_{0.25}$As.

Determination of the internal electric field intensity from the period of FKOs for the sample from Fig. 2 results in a value of $F = 6.6 \pm 0.3$ kV/cm. Since the In$_{0.75}$Ga$_{0.25}$As layer is capped with 200 nm of In$_{0.75}$Al$_{0.25}$As, the observed electric field is not related to the surface states, but rather to a heterointerface within the metamorphic structure. Therefore, an active region grown inside the In$_{0.75}$Ga$_{0.25}$As waveguide will be placed into a strong built-in electric field, which will undoubtedly affect the efficiency of future mid-IR emitters.

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5. References

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