Photovoltaic Detector Based on Type II Heterostructure with Deep AlSb/InAsSb/AlSb Quantum Well in the Active Region for the Mid-Infrared Spectral Range

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Abstract. Photodetectors for the spectral range 2-4 μm, based on an asymmetric type-II heterostructure p-InAs/AlSb/InAsSb/AlSb(p, n)-GaSb with a single deep quantum well (QW) or three deep QWs at the heterointerface, have been grown by metal-organic vapor phase epitaxy and analysed. The transport, luminescent, photoelectric, current-voltage, and capacitance-voltage characteristics of these structures have been examined. A high-intensity positive and negative luminescence was observed in the spectral range 3-4 μm at high temperatures (300–400 K). The photosensitivity spectra were in the range 1.2-3.6 μm (T = 77 K). Large values of quantum efficiency (η = 0.6-0.7), responsivity (Sλ = 0.9-1.4 A·W−1), and detectivity Dλ = 3.5·1011 to 1010 cm·Hz1/2·W−1 were obtained at T = 77-200 K. The small capacitance of the structures (C = 1.5 pF at V = −1 V and T = 300 K) enabled an estimate of the response time of the photodetector at τ = 75 ps, which corresponds to a bandwidth of about 6 GHz. Photodetectors of this kind are promising for heterodyne detection of the emission of quantum-cascade lasers and IR spectroscopy.

1. Introduction
In recent years, considerable attention has been given to development of new types of photodetectors for the mid-IR spectral range on the basis of heterostructures with quantum wells (QWs) in order to improve their parameters (make lower dark currents, improve the operation speed, etc. [1]). Fabrication of quantum-well photodiodes based on GaAs/AlGaAs and InGaAs/SbP double-barrier heterostructures for the wavelength range 3-5 μm has been reported [2, 3]. Photodiodes of this kind are promising for heterodyne detection and free-space communication systems. The spectral range 2-5 μm is also important for gas analysis, ecological monitoring, and medical diagnostics. One advantage of QW IR photodiodes is their fast response (on the order of several picoseconds [1]).

Free-space detection requires a bandwidth exceeding 10-20 GHz. In this case, information is transmitted by quantum-cascade lasers for which the recording time is limited by the slow response of the existing photodetectors. Another advantage of QW photodiodes is their operation under small biases with low dark currents and, accordingly, with a low noise level. Research and development work on such photodetectors has been underway for more than 15 years. The InAs(Sb)-AlSb system has a unique band diagram because of the large conduction band offset ΔEC > 1.35 eV, ΔEv = 0.15 eV and the possibility of fabrication of deep QWs [4]. This is a new promising material for optoelectronic devices, quantum-cascade lasers, field-effect transistors, and resonant-tunneling diodes [5-7].

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This communication reports on the fabrication and study of a photovoltaic detector operating in the spectral range 2-4 μm based on an asymmetric type-II heterostructure p-InAs/AlSb/InAsSb/AlSb/(p, n)-GaSb with a single deep QW or several QWs at the interface.

2. Procedures for fabrication and study of the photodiodes

Nanoheterostructures containing one or three QWs, 20-nm AlSb/5-nm InAs$_{0.84}$Sb$_{0.16}$/20 nm AlSb, and 0.5-μm-thick (p, n)-GaSb capping layers were grown on p-type InAs:Mn (100) substrates by low-pressure metal-organic vapor-phase epitaxy (LP-MOVPE) in an AXTRON-200 installation at a temperature of 500°C in the atmosphere of hydrogen at the MOVPE laboratory of the Institute of Physics, Czech Academy of Sciences [8]. The band diagram of a structure with three QWs is shown in Fig. 1. The capping GaSb layer was nominally undoped, whereas the InAs substrate was doped with a Mn acceptor impurity to a concentration $p = 10^{17}$ cm$^{-3}$ at $T = 300$ K. In structures with one or three QWs and 20-nm-thick AlSb barriers, the width of the InAsSb QWs was 5 nm. At $T < 100$ K, the substrate became a semi-insulator, which enabled magnetotransport measurements.

The magnetotransport properties of the structures were studied with rectangular samples with the Hall configuration and six ohmic contacts in fields of up to 5 T at a low temperature $T = 77.4$ K. The Hall mobility in the sample with a single 5-nm-wide AlSb/InAs$_{0.84}$Sb$_{0.16}$/AlSb QW grown on a p-InAs:Mn (100) substrate was $\mu = 5000$ cm$^2$·V$^{-1}$·s$^{-1}$. The results of these measurements demonstrated that an n-type channel similar to that we observed previously [9] exists at the type-II p-InAs/AlSb interface. The transport broadening [10] $2\Gamma = 2h/\tau$, where $\tau = \mu m^*/e = 10^{-13}$ s, was estimated at an effective electron mass in the InAsSb solid solution $m^* = 0.016m_0$. A value $2\Gamma = 16$ meV was obtained by taking into account the fact that the mobility is governed by scattering at interfacial irregularities [11]. As noted in [10], the value of $2\Gamma$ for the double InAs/AlSb heterostructure is related to the linewidth of intersubband transitions and well agrees with the data for our structure with a QW calculated from the half-width of the luminescence spectrum of a structure of this kind, $\Delta h\nu = 21$ meV at $T = 77.4$ K, found from the data of [12]. These results are indicative of the good quality of the heterointerface in the MOVPE-grown QW structures.

To study the electroluminescent, electrical, and photoelectric properties, we fabricated structures by means of standard photolithography and wet etching as mesa diodes with a sensitive area diameter of 300 μm. Electroluminescence (EL) spectra were recorded with a Digikrom-480 monochromator, Stanford S-580 phase-lock detector, and cooled InSb photodiode (Judson Ltd.). To stabilize measurements at temperatures above 300 K, the diodes were mounted on a special holder with a thermoelectric cooler.

The photosensitivity spectra were studied in the temperature range 77-300 K with an SPM-2 monochromator and a globar as a source of light. The quantum efficiency was evaluated by comparison with the sensitivity of a calibrated Carl Zeiss thermopile.

![Figure 1. Band diagram of an asymmetric heterostructure with 3 deep AlSb/InAsSb/AlSb QWs at the interface.](image-url)
3. Results and discussion

A study of the EL spectra in the temperature range 77–300 K revealed a high intensity of both positive and negative EL under a forward or reverse bias (minus at the p-substrate), respectively, at photon energies of 0.3-0.4 eV [12].

Figure 2 shows spectra of positive and negative EL for a structure p-InAs/AlSb/InAsSb/AlSb/p-GaSb at T = 28 and 106 °C. The temperature dependence of the optical power of the positive and negative EL at high temperatures (300-380 K) at a drive current i = 200 mA is shown in Fig. 3. It can be seen that the power of the negative EL increases and that of the positive EL decreases with increasing temperature. The high efficiency of the negative EL is due to the decrease in the intensity of nonradiative Auger recombination with increasing temperature. Moreover, as shown in [13], the Auger recombination can be suppressed at the type-II heterointerface. This makes it possible to use this structure by converting it to the light-emitting diode or photodiode mode at high temperatures. The current-voltage (I-V) characteristics of the structures under study, shown in Fig. 4, were of rectifying type and corresponded to an abrupt heterojunction. The dark currents for a triple-well structure were lower than those for the structure with a single well (see table 1).

The differential resistance was calculated from the I-V characteristics at small near-zero biases for structures with single and triple QWs at three temperatures of 77, 250, and 300 K. The measurement results are listed in the table, together with the R0A products, where A is the size of the sensitive area of the mesa diode. Normalized spectral photosensitivity characteristics at T = 77 and 295 K are shown in Fig. 5 for structures with a single QW. The photosensitivity spectra were localized in the wavelength range 1.0-3.4 μm at T = 77 K and 1.2-3.8 μm at 295 K. The nature of the spectrum corresponds to that of the p-InAs/p(n)-GaSb heterojunction. The single-well structure shows an additional weak peak at 4.0-4.5 μm. It is noteworthy that a similar long-wavelength peak has also been observed previously in negative-EL spectra and its spectral position remained the same on changing the bias polarity [12]. We believe that this peak is due to the transition from the surface state of a Mn acceptor located close to the interface [13]. The absolute sensitivity at the peak of the spectrum for a sample with three QWs at the heterointerface was 1.5 times that of single-well structures in the photovoltaic mode. On applying a small positive bias, the photoresponse signal somewhat increased. It can be seen in the table that, as the temperature was raised from 77 to 300 K, the photosensitivity decreased by three orders of magnitude in accordance with changes in the differential resistance. The dark currents in the triple-well structures were lower than those in structures with a single QW. For example, the reverse current density at T = 77 K and V = −0.4 V was J1 = 5.5·10−2 and J3 = 3.4·10−2 A·cm−2 for single- and triple-well heterostructures, respectively.

![Figure 2. Spectra of the positive and negative electroluminescence from a p-InAs/AlSb/InAsSb/AlSb/p-GaSb heterostructure under forward (“+”) at p-InAs) and reverse (“−”) at p-InAs) biases at a drive current i = 50 mA and two temperatures T: (1, 1’) +28°C and (2, 2’) +106°C.](image)

![Figure 3. Temperature dependences of the EL intensity for a p-InAs/AlSb/InAsSb/AlSb/p-GaSb heterostructure with a single QW. (1) Positive EL (forward bias) and (2) negative EL (reverse bias). Drive current i = 200 mA.](image)
In the photovoltaic mode, the photosensitivity and quantum efficiency were estimated as $S_\lambda = 0.9 - 1.4 \text{ A W}^{-1}$ and $\eta = 0.6 - 0.7$. The equivalent noise power (with only the dark noise taken into account) and detectivity of the single-well photodiode were calculated at the peak of the spectrum at $\lambda = 3 \mu m$ and $T = 77$ K by using the known relations. We obtained $\text{NEP} = 6 \times 10^{-14} \text{ W Hz}^{-1/2}$ and $D_\lambda^* = 3.5 \times 10^{11} \text{cm Hz}^{1/2} \text{ W}^{-1}$. The detectivity varied within the temperature range 77-200 K from $3.5 \times 10^{11}$ to $10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$.

The large value of the detectivity of the photovoltaic detector based on the MOVPE-grown asymmetric type-II heterostructure $p$-$\text{InAs/AlSb/InAsSb/AlSb/}(p, n)$-$\text{GaSb}$ with a deep quantum well at the heterointerface is comparable with the parameters of MBE-grown photodiodes based on $p$--$n$-$\text{InAs}$ superlattices and QW detectors based on $\text{GaAlAs/GaAs}$ and $\text{InGaAs/InP}$ double heterostructures [1] operating in the spectral range 2-3 $\mu m$, as well as with the parameters of commercial InAs photodiodes.

**Figure 4.** I-V characteristics of a heterophotodiode with 3 QWs in the active region at small biases. $T = 77$ and 295 K.

Analysis of the capacitance–voltage characteristics demonstrated a marked difference between the parameters of structures with single and triple QWs at the heterointerface (Fig. 6). In the single-well structure, the capacitance weakly changed within the range $C = 200$-300 pF as the reverse bias was varied from 0 to 1 V. An interesting feature was that the capacitance sharply decreased from $C = 200$ pF at zero bias to 1.5 pF at $T = 300$ K for the triple-well photodiodes. These values

**Figure 5.** Normalized photosensitivity spectra for a photodiode with a single QW at $T = 77$ and 295 K.

**Figure 6.** Capacitance vs. the reverse bias for a heterophotodiode with (1) single QW and (2) 3 QWs at $T = 300$ K.
correspond to a response time $R_L C = 75 \text{ ps}$ at a load $R_L = 50 \Omega$. Such a behavior of the capacitance can be accounted for by the fact that, in the case of a series connection of several capacitors, the total capacitance is always smaller than the capacitance of any capacitor in the circuit. Indeed, we have in the triple-well sample several series connected p–n junctions containing four AlSb barriers. The operation speed must be independent of the sample area. Thus, we have in our case a fast photodiode with a bandwidth of $\sim 10 \text{ GHz}$. Previously, we have described fast-response p–i–n photodiodes based on bulk GaInAsSb/AlGaAsSb heterostructures for the spectral range 1.6-2.4 $\mu$m, with a bandwidth of about 2 GHz [14], and avalanche photodiodes for the spectral range 2-4 $\mu$m [15]. The photodiodes with QWs in the active region, examined in this study, are promising for application in heterodyne detection of the emission of quantum-cascade lasers, information networks, medical diagnostics, and ecological monitoring.

**Table 1.** Dark currents and differential resistance at zero bias voltage for structures with one and 3 QWs at the heterointerface.

| Parameter                      | Single-well structure N 1322 | Triple-well structure N 1323 |
|--------------------------------|-------------------------------|-----------------------------|
|                                | $T = 300 \text{ K}$          | $T = 77 \text{ K}$         |
| Differential resistance        |                               |                             |
| $R_0$, $\Omega$, at 10 mV      | 28                            | 26·$10^3$                   |
| $R_0$, $\Omega \cdot \text{cm}^2$ | $2.0 \cdot 10^{-2}$           | 1.8                        |
| Dark current $I_d$, $\text{A}$ at $V = -0.2 \text{ V}$ | $2.4 \cdot 10^{-3}$           | $1.5 \cdot 10^{-5}$        |
|                                | $2.8 \cdot 10^{-3}$           | $7.2 \cdot 10^{-5}$        |
| $V = -0.6 \text{ V}$           |                               |                             |
| $10^{-3}$                      | $1.0 \cdot 10^{-3}$           | $1.2 \cdot 10^{-5}$        |
| $V = -0.6 \text{ V}$           | $1.0 \cdot 10^{-3}$           | $1.2 \cdot 10^{-5}$        |

4. Conclusions

Asymmetric type-II p-InAs/AlSb/InAsSb/AlSb/(p, n)-GaSb heterostructures with one and 3 quantum wells at the heterointerface were grown by metal-organic vapor-phase epitaxy and their luminescent, transport, and photoelectric properties were studied. A high-intensity positive and negative electroluminescence was observed in the spectral range 3-4 $\mu$m at $T = 300-380 \text{ K}$. A study of the temperature dependence of the positive and negative luminescence demonstrated that the light-emitting structures described in the communication can operate at high temperatures in the light-emitting diode/photodiode mode upon switching the bias voltage.

The spectral, current-voltage, and capacitance-voltage characteristics of mesa photodiodes with AlSb/InAsSb/AlSb quantum wells in the active region were for the first time studied in detail in the temperature range 77-300 $\text{ K}$ in the wavelength range 1-4 $\mu$m. Large values of the monochromatic responsivity ($S_\lambda = 0.9-1.4 \text{ A} \cdot \text{W}^{-1}$) and quantum efficiency ($\eta = 0.6-0.7$) were obtained, and the detectivity was estimated at $3.5 \cdot 10^{11}$ to $10^{10}$ $\text{cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$ at $T = 77-200 \text{ K}$. A sharp decrease in the diode capacitance with the reverse bias ($C = 1.5 \text{ pF}$ under a reverse bias $V = -1 \text{ V}$, $T = 300 \text{ K}$) was observed for the detector with three quantum wells in the active region, which corresponds to a response time of 75 ps and a bandwidth exceeding 6 GHz. The parameters of the quantum-well photodiodes in the active region examined in this study are comparable with characteristics of quantum-well photodiodes based on InGaAs/InP and GaAlAs/GaAs heterostructures grown by molecular beam epitaxy, as well as with parameters of commercial p-n InAs/InAsSbP photodiodes, but surpass these in operation speed.
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