VILNIUS UNIVERSITY

CENTER FOR PHYSICAL SCIENCES AND TECHNOLOGY

SEMICONDUCTOR PHYSICS INSTITUTE

VIKTORIJA NARGELIENĖ

RESEARCH AND APPLICATION OF GaAs/$Al_xGa_{1-x}As$ HETEROSTRUCTURES FOR MICROWAVE DETECTION

Summary of doctoral thesis

Physical sciences, physics (02 P), semiconductor physics (P 265)

Vilnius 2013

The research has been carried out in 2008 – 2013 at the Department of Electronics of Semiconductor Physics Institute, Center for Physical Sciences and Technology

Scientific supervisor:

Prof. Dr. Algirdas Sužiedėlis (CPST Semiconductors Physics Institute, Physical sciences, physics – 02 P, semiconductor physics – P 265)

Consultants:

Prof. Habil. Dr. Algis Jurgis Kundrotas (CPST Semiconductors Physics Institute, Physical sciences, physics – 02 P, semiconductor physics – P 265)

Dr. Edmundas Širmulis (CPST Semiconductors Physics Institute, Physical sciences, physics – 02 P, semiconductor physics – P 265)

Council of defence of the doctoral thesis of Physical Sciences at Vilnius University:

Chairman:

Habil. Dr. Žilvinas Kancleris (CPST Semiconductors Physics Institute, Physical sciences, physics – 02 P, semiconductor physics – P 265)

Members:

Prof. Habil. Dr. Jūras Banys (Vilnius University, Physical sciences, physics – 02 P, semiconductor physics – P 265)

Prof. Dr. Vytautas Kleiza (Kaunas University of Technology, Physical Sciences, mathematics – 01 P, mathematical and general theoretical physics, classical mechanics, quantum mechanics, relativity, gravitation, statistical physics, thermodynamics – P 190)

Prof. Dr. Jurij Novickij (Vilnius Gediminas Technical University, Technological Sciences, electrics and electrical engineering – 01T, electrical engineering – T 190)

Doc. Dr. Voitech Stankevič (CPST Semiconductors Physics Institute, Physical sciences, physics — 02 P, semiconductor physics – P 265)

Opponents:

Prof. Habil. Dr. Saulius Balevičius (CPST Semiconductors Physics Institute, Physical sciences, physics — 02 P, semiconductor physics – P 265)

Prof. Habil. Dr. Eugenijus Šatkovskis (Vilnius Gediminas Technical University, Physical sciences, physics — 02 P, semiconductor physics – P 265)

The official defence of doctoral thesis will be held in public session of Vilnius University Defence Council of Physical Sciences at 14 h on December 20, 2013 in the Conference hall of Semiconductor Physics Institute (Center for Physical Sciences and technology), A. Goštauto 11, LT – 01108 Vilnius, Lithuania.

The summary of doctoral thesis has been distributed on November 20, 2013.

The doctoral thesis is available at the libraries of Vilnius University and Center for Physical Sciences and Technology.

VILNIAUS UNIVERSITETAS

FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS

PUSLAIDININKIŲ FIZIKOS INSTITUTAS

VIKTORIJA NARGELIENĖ

ĮVAIRIATARPIŲ GaAs/$Al_xGa_{1-x}As$ DARINIŲ TYRIMAI IR TAIKYMAI MIKROBANGŲ DETEKCIJAI

Daktaro disertacijos santrauka

Fiziniai mokslai, fizika (02 P), puslaidininkių fizika (P 265)

Vilnius 2013

Disertacija rengta 2008 – 2013 metais FTMC Puslaidininkių fizikos instituto Elektronikos skyriuje.

Mokslinis vadovas:

Prof. dr. Algirdas Sužiedėlis (FTMC Puslaidininkių fizikos institutas, fiziniai mokslai, fizika – 02 P, puslaidininkių fizika – P 265)

Konsultantai:

Prof. habil. dr. Algis Jurgis Kundrotas (FTMC Puslaidininkių fizikos institutas, fiziniai mokslai, fizika – 02 P, puslaidininkių fizika – P 265)

Dr. Edmundas Širmulis (FTMC Puslaidininkių fizikos institutas, fiziniai mokslai, fizika – 02 P, puslaidininkių fizika – P 265)

Disertacija ginama Vilniaus Universiteto Fizikos mokslų krypties taryboje:

Pirmininkas:

Habil. dr. Žilvinas Kancleris (FTMC Puslaidininkių fizikos institutas, fiziniai mokslai, fizika – 02 P, puslaidininkių fizika – P 265)

Nariai:

Prof. habil. dr. Jūras Banys (Vilniaus universitetas, fiziniai mokslai, fizika – 02 P, puslaidininkių fizika – P 265)

Prof. dr. Vytautas Kleiza (Kauno technologijos universitetas, fiziniai mokslai, matematika – 01 P, matematinė ir bendroji teorinė fizika, klasikinė mechanika, kvantinė mechanika, reliatyvizmas, gravitacija, statistinė fizika, termodinamika – P 190)

Prof. dr. Jurij Novickij (Vilniaus Gedimino technikos universitetas, technologiniai mokslai, elektros ir elektronikos inžinerija – 01 T, elektros inžinerija – T 190)

Doc. dr. Voitech Stankevič (FTMC Puslaidininkių fizikos institutas, fiziniai mokslai, fizika – 02 P, puslaidininkių fizika – P 265)

Oponentai:

Prof. habil. dr. Saulius Balevičius (FTMC Puslaidininkių fizikos institutas, fiziniai mokslai, fizika – 02 P, puslaidininkių fizika – P 265)

Prof. habil. dr. Eugenijus Šatkovskis (Vilniaus Gedimino technikos universitetas, fiziniai mokslai, fizika – 02 P, puslaidininkių fizika – P 265)

Disertacija bus ginama viešame Fizikos mokslų krypties tarybos posėdyje 2013 m. gruodžio mėn. 20 d. 14 valandą Fizinių ir Technologijos mokslų centro Puslaidininkių fizikos instituto posėdžių salėje A. Goštauto 11, LT – 01108 Vilnius, Lietuva.

Disertacijos santrauka išsiuntinėta 2013 m. lapkričio mėn. 20 d.

Disertaciją galima peržiūrėti Vilniaus universiteto bei Fizinių ir technologijos mokslų centro bibliotekose.

List of abbreviations, used in the text

MBE – molecular beam epitaxy

LPE – liquid phase epitaxy

PL – photoluminescence

TCSPC – time correlated single photon counting

Introduction

The term millimeter waves is usually used to describe the spectrum region from 30 GHz to 300 GHz where the wavelengths is of the order of millimeter. This region is attractive in various applications for a number of reasons. First of all, there is a large amount of spectrum available which is inherent to high frequency range. Secondly, some of the wavelengths have special propagation properties in atmosphere: some of them are strongly attenuated, while the others can propagate with very little attenuation. Millimeter waves are used in telecommunications, military, automobile and for medical applications.

Every microwave receiver consists of rectifying element which converts the high frequency of input signal to low frequency or zero frequency signal. This element is usually a two terminal device – mixer, or detector diode.

Since the beginning of 20th century Schottky diode was used for the signal mixing and detection [1, 2]. However, the main disadvantage of this diode was the need for external bias. The need for diodes operating without the external bias led to development of technologies for new rectifying devices fabrication. A number of new two terminal rectifying devices was proposed. A semiconductor device – the hot carrier microwave diode was also proposed [3]. Although the sensitivity of this diode was much less than that of the Schottky diode, the operating frequency range was beyond the millimeter waves. All microwave diodes are characterized by their sensitivity, noise properties and operating frequency range. Nowadays the scientific research of microwave diodes is mainly focused on extending the operating frequency range and increasing their sensitivity to microwaves.

Considering the issues mentioned above the **main goal** of this thesis was to create microwave diodes on the base of GaAs/$Al_xGa_{1-x}As$ semiconductor heterostructures and to investigate their detection properties in millimeter wavelength range of electromagnetic radiation.

Main objectives

- To grow GaAs/$Al_xGa_{1-x}As$ structures using liquid phase epitaxy and molecular beam epitaxy growths method.
- To characterize GaAs/$Al_xGa_{1-x}As$ epitaxial layers using photoluminescence and time correlated single photon counting techniques.
- To fabricate planar asymmetrically necked microwave diodes, using epitaxial GaAs/$Al_{0,25}Ga_{0,75}As$ layers having different doping profile of $Al_{0,25}Ga_{0,75}As$ barrier layer.
- To fabricate rectifying microwave diodes using epitaxial GaAs/$Al_xGa_{1-x}As$ layers having different AlAs mole fraction x.
- To investigate electrical properties of microwave diodes using current-voltage characteristics.
- To investigate detection properties of microwave diodes in a wide frequency range from 8 GHz to 170 GHz.

Novelty and significance of the thesis

- Detection properties of planar asymmetrically necked microwave diodes fabricated using selectively doped GaAs/$Al_{0,25}Ga_{0,75}As$ heterostructures were investigated in broad frequency range up to terahertz region. Dependence of detection properties on doping profile of $Al_{0,25}Ga_{0,75}As$ barrier layer was estimated.
- Detection properties of rectifying GaAs/$Al_xGa_{1-x}As$ microwave diodes in the millimeter frequency range were investigated. Dependence of detection properties on AlAs mole fraction x was estimated.
- Influence of intervalley electromotive force in the detected signal of the point contact GaAs/$Al_{0,3}Ga_{0,7}As$ microwave diode was evidenced.

Statements to defend:

- Microwave detection in point-contact GaAs/$Al_{0,3}Ga_{0,7}As$ microwave diodes, fabricated by liquid phase epitaxy, is generally due to microwave rectification and intervalley electromotive force.
- Sensitivity of planar asymmetrically necked GaAs/$Al_{0,25}Ga_{0,75}As$ microwave diodes is increased with decreasing the cross sectional area of the active region of the diodes and decreasing the thickness of barrier layer doping profile.
- Microwave detection of planar GaAs/$Al_xGa_{1-x}As$ microwave diodes having AlAs mole fraction $x = 0{,}25 \div 0{,}1$, fabricated by molecular beam epitaxy, is due to microwave rectification and sensitivity depends on the AlAs mole fraction. Largest sensitivity was obtained in diodes, with AlAs mole fraction $x = 0{,}2$.

Layout of the thesis

The thesis consists of four chapters. The articles and conference contribution of the author together with co-authors are listed at the beginning of the thesis. The thesis is finalized by the conclusions. The layout of the thesis is organized as follows.

1. Review of scientific literature

This chapter is a short review of microwave detection methods and scientific research of various microwave diodes. Special emphasis is put on detection mechanisms due to microwave rectification, thermo electromotive force, bigradient electromotive force, and intervalley electromotive force of hot carriers. Properties of isotype GaAs/AlGaAs heterojunctions, as well as two transport mechanisms – parallel and perpendicular to the heterojunction are reviewed.

2. Fabrication of microwave diodes

Design of semiconductor structures and fabrication process of microwave diodes are presented in this chapter.

Bulk semiconductors used for microwave applications include germanium, silicon, silicon carbide, gallium arsenide and indium phosphide. Electronic properties of these materials determine the appropriate frequency range for a particular material. The frequency range can be extended through the use of the “bandgap engineering”. Silicon is the most widely used semiconductor to make electronic devices, however, there are semiconductor compounds that perform functions beyond the physical limits of the electronic properties of silicon. Most common material combinations used in microwave electronics come from the group III and group V elements.

We have chosen GaAs/$Al_xGa_{1-x}As$ semiconductor structure for our devices fabrication. Five different structures were grown using LPE and MBE methods. Growth methods and main characteristics of heterostructures are summarized in Table 1.

Table 1. Growth methods and main parameters of GaAs/$Al_xGa_{1-x}As$ heterostructures. N_{Si} ($Al_xGa_{1-x}As$)– donor density in silicon doped $Al_xGa_{1-x}As$ layer, d_{Si} – thickness of Si doped $Al_xGa_{1-x}As$ layer, d_{sp} – thickness of undoped $Al_xGa_{1-x}As$ layer (spacer).

Sample	**AlAs mole fraction *x* in $Al_xGa_{1-x}As$ layer**	**Donor type**	**N_{D1} (GaAs), cm^{-3}**	**N_{D2} ($Al_xGa_{1-x}As$), cm^{-3}**	**d_D (nm)**	**d_{sp} (nm)**	**Growth method**	**Growth temp. (°C)**
H1	0,25	Si	-	4×10^{17}	70	7,5	MBE	600
H2	0,25	Si	-	3×10^{18}	8,5	7,5	MBE	600
T1	0,3	Te	1×10^{15}	2×10^{16}	5000	-	LPE	800
V1	0,2	Si	1×10^{16}	1×10^{16}	300	-	MBE	600
V2	0,3; 0,25; 0,2; 0,1	Si	1×10^{16}	1×10^{16}	300	-	MBE	700

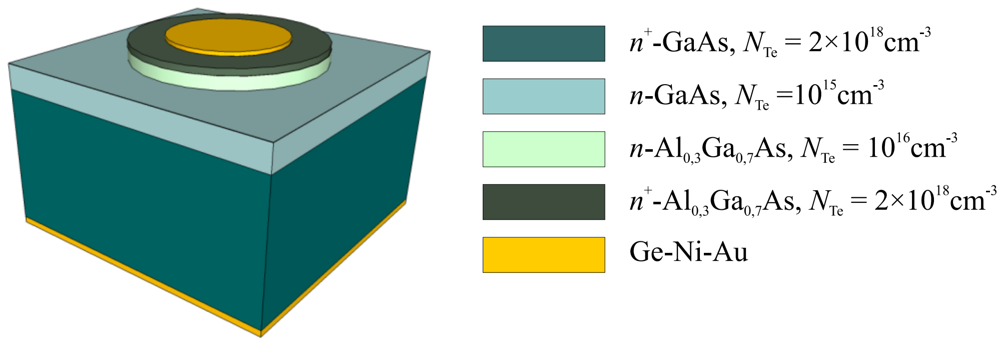


Figure 1. Point contact GaAs/$Al_{0,3}Ga_{0,7}As$ microwave diode T1.

H1, H2, T1 and V1 represent unique structure, while V2 represents a series of structures having identical layout and growth technique, but different AlAs mole fraction in $Al_xGa_{1-x}As$ layers.

Chemical etching, thermal metal evaporation, rapid thermal annealing, polymere coating and mechanical polishing techniques were used for the diode fabrication. Point contact microwave diodes shown in Figure 1 were fabricated using heterostructure T1. The diameter of small area mesa was 15 µm. Ohmic contacts of the diode were deposited on the conductive substrate and on the top n^+-$Al_{0,3}Ga_{0,7}As$ layer causing electron transport perpendicular to the epitaxial layers.

Planar asymmetrically necked microwave diodes shown in Figure 2 were fabricated using heterostructures H1 and H2. Diodes having different neck width (1 µm, 2 µm, 3 µm

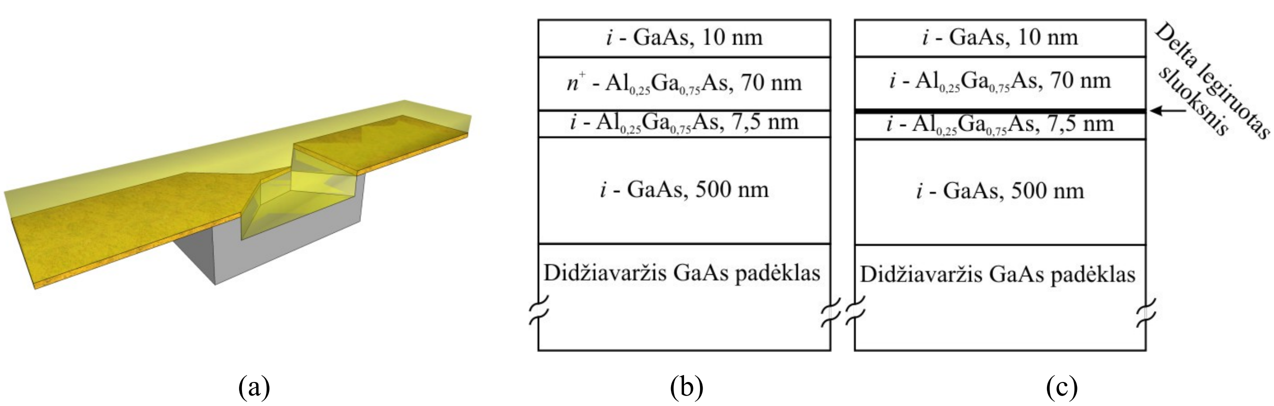
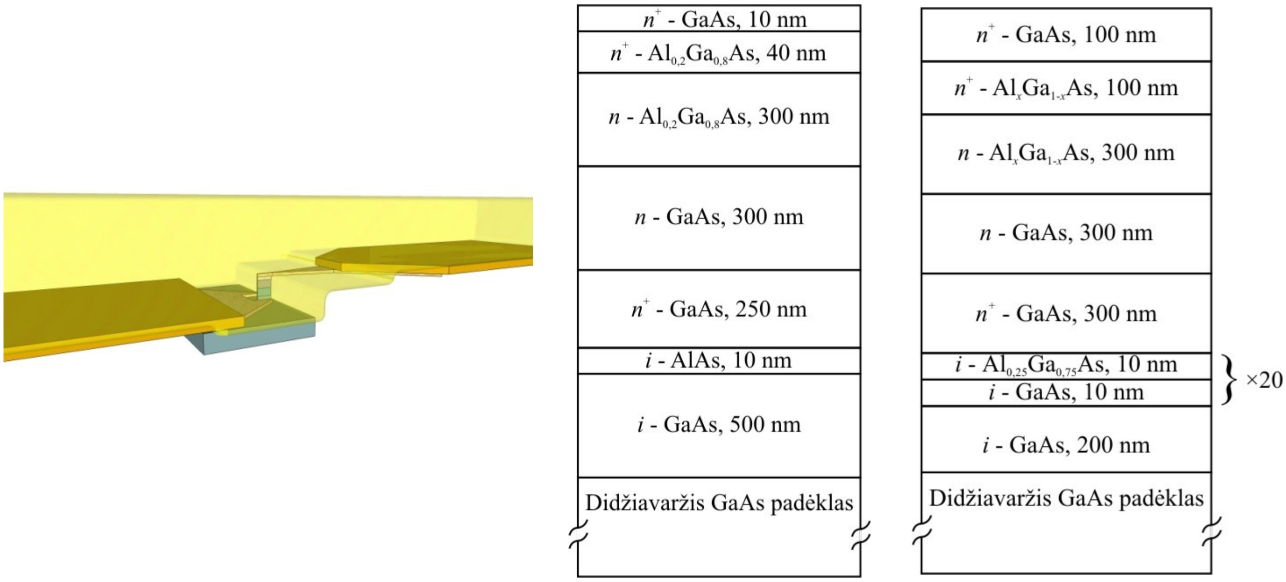


Figure 2. Planar asymmetrically necked GaAs/$Al_{0,25}Ga_{0,75}As$ diode (a) fabricated using selectively doped heterstructure H1 (b) and H2 (c).



(a) (b) (c)

Figure 3. Planar rectifying microwave diode (a) fabricated using heterostructures V1 (a) and V2 (b).

and 4 μm) were fabricated. Since ohmic contacts of H1 and H2 microwave diodes lie on the same epitaxial layer, the current transport is parallel to epitaxial layers.

Planar rectifying microwave diodes shown in Figure 3 were fabricated using heterostructures V1 and V2.

Diodes having different cross section areas were fabricated. Ohmic contacts in these diodes lie on different epitaxial layers (n^+-GaAs and n^+-AlGaAs), therefore current transport is perpendicular to the epitaxial layers in the same manner as in the point contact diode.

3. Characterization of samples

This chapter presents experimental investigation of epitaxial GaAs/$Al_xGa_{1-x}As$ structures using photoluminescence and time correlated single photon counting techniques (TCSPC). Electrical properties evaluated from current-voltage characteristics are also presented.

Figure 4 depicts the dependence of PL intensity of T1 heterostructure on photon energy at liquid helium temperature. Peaks in the PL spectra are prescribed to GaAs and

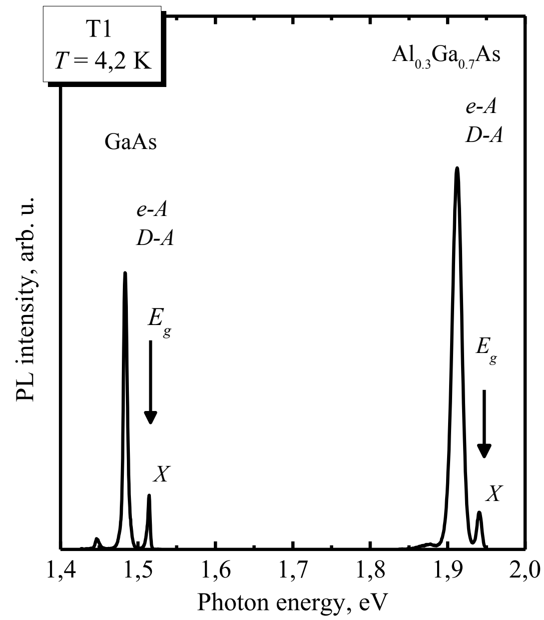


Figure 4. PL spectra of T1 heterostructure measured at liquid helium temperature.

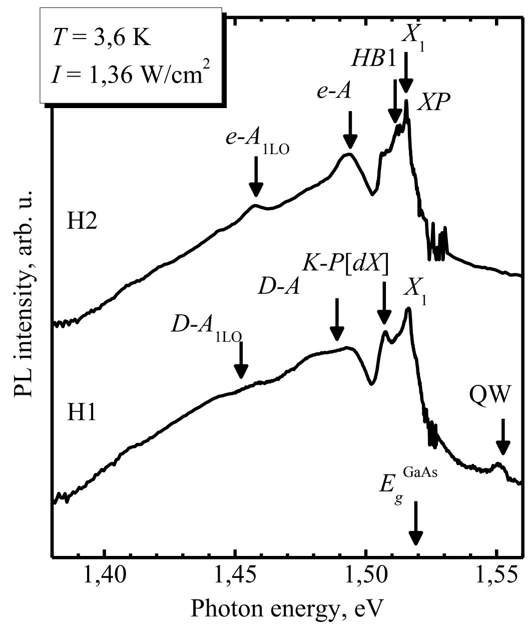


Figure 5. PL spectra of H1 and H2 heterostructures, measrued at 3,6 K temperature at 1,36W/cm^2 laser excitation intensity.

$Al_{0.3}Ga_{0.7}As$ layers. The most intensive peaks are attributed to free electron transition to the acceptor level (*e–A*) as well as to electron transition from the donor to the acceptor energy level (*D–A*). Free exciton PL peaks *X* in GaAs and $Al_{0.3}Ga_{0.7}As$ layers evidence good quality of the epitaxial layers. The values of energy gap E_g at liquid helium temperature were reconstructed from exciton energy by taking into account an exciton binding energy of 4 meV and 6 meV in the case of GaAs and $Al_{0.3}Ga_{0.7}As$, respectively [4].

The reconstructed E_g values are in good agreement with the experimental results of a previous work [5]: E_g = 1.519 eV for GaAs and E_g = 1.947 eV for $Al_{0.3}Ga_{0.7}As$ alloy.

The spectra of H1 and H2 structures measured at liquid helium temperature are presented in Figure 5. Two groups of PL bands in the measured spectra can be clearly resolved. The most intensive line X_1 is attributed to the first excitonic transition. The *XP* line is attributed to the exciton-polariton transition. *e-A* is the free electron-neutral residual acceptor transition, whereas e-A_{1LO} depicts the first phonon replica of the *e-A* transition. *D-A* and D-A_{1LO} indicate the residual donor to residual acceptor transitions and their first LO phonon replica, respectively. *HB*1 is the first emission band that is typical for selectively doped heterostructures and it results from an intrinsic 2D excitonic emission [6, 7]. *K-P*[*dX*] region within 1.504–1.511 eV is attributed to defect-bound exciton emission and is also called the Künzel–Ploog region [8].

The PL spectra of GaAs/$Al_xGa_{1-x}As$ structures V2 with a different Al mole fraction x at a temperature of 3.6 K and a laser excitation intensity of I = 1.36 W/cm^2 are presented in Figure 6. One can resolve two parts of the spectra indicated by segments. The first one, below 1.57 eV, is attributed to the GaAs layers. An emission below the forbidden energy gap, E_g(GaAs) =1.519 eV, is related to the lightly doped GaAs layer. The lower energy transitions at 1.49 eV, labeled A, are the recombination of free electron with the residual acceptor. The transition at 1.515 eV is a well-known free exciton line [5] (marked as X in Figure 6). The broad band from 1.5 to 1.57 eV is attributed to the emission from the heavily

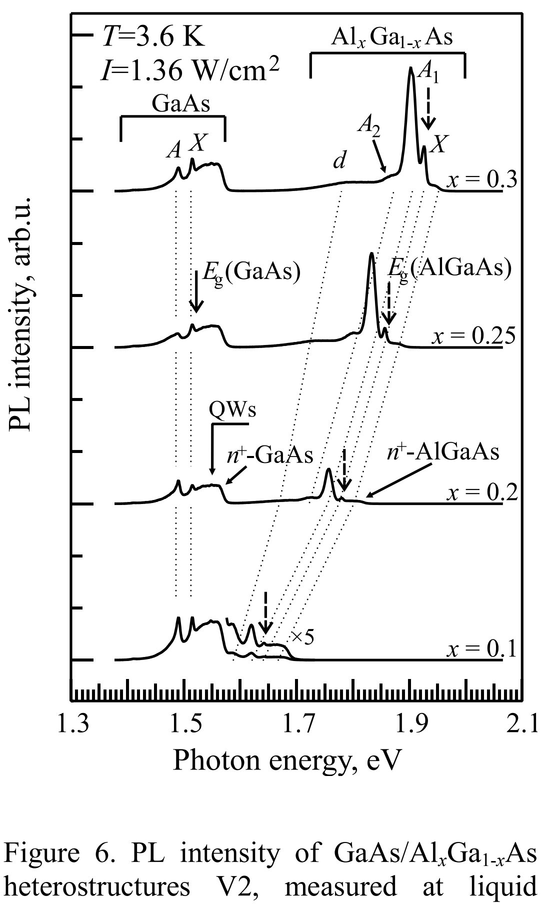


Figure 6. PL intensity of GaAs/$Al_xGa_{1-x}As$ heterostructures V2, measured at liquid nitrogen temperature and laser excitation intensity of I = 1,36 W/cm^2. The spectra are shifted along the vertical axis for clarity.

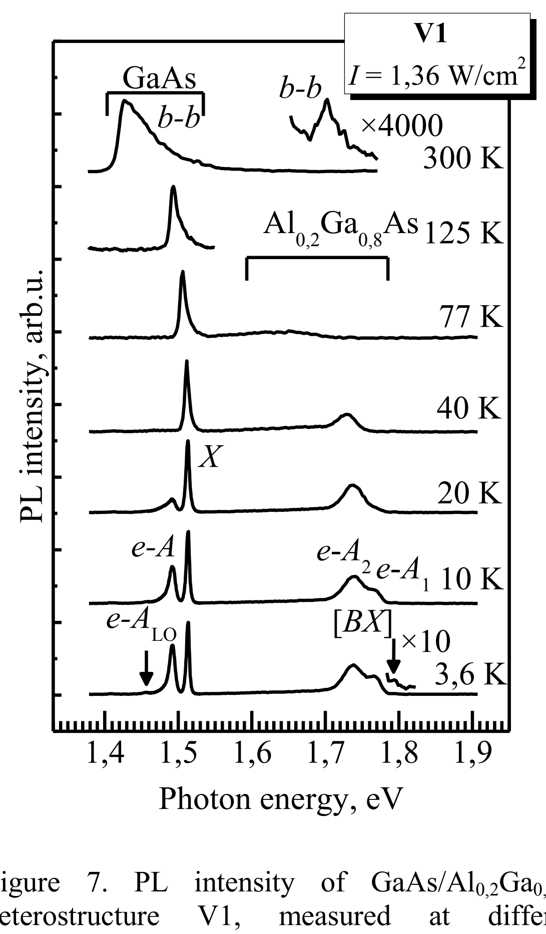


Figure 7. PL intensity of GaAs/$Al_{0,2}Ga_{0,8}As$ heterostructure V1, measured at different temperatures and laser excitation intensity of I = 1,36 W/cm^2. The spectra are shifted along the vertical axis for clarity.

doped GaAs layer (n^+-GaAs). This broad band nearly disappeared from the spectra when the top n^+-GaAs layer was removed by etching.

The second part of the PL spectra is associated with the $Al_xGa_{1-x}As$ layers. It can be shown that the PL intensity from $Al_xGa_{1-x}As$ decreases with the decrease of the AlAs mole fraction. This part of the PL spectrum can be interpreted as the superposition of two separate spectra arising from both the n^+-type and the n-type $Al_xGa_{1-x}As$ layers. As Figure 6 shows, this part of the spectrum consists of five broad peaks for the samples with AlAs mole fraction $x = 0{,}3$, $x = 0{,}25$ and $x = 0{,}2$. Only four peaks are observed in the spectrum of the $Al_xGa_{1-x}As$ in sample with AlAs mole fraction $x = 0{,}1$.

The energetic positions of possible emission lines have been theoretically calculated and compared with experimental results. Due to an amphoteric nature of Si impurity, the Si-acceptor on the As site can also be expected in the n-type Si-doped $Al_xGa_{1-x}As$. An unintentional impurity that is commonly observed in GaAs and $Al_xGa_{1-x}As$ alloys grown by MBE is carbon (C). Consequently, we used the dependence of impurity binding energy in $Al_xGa_{1-x}As$ in the composition range of $0 < x < 0.4$ as:

$$E_{Si}(D) = 6.0 + 8.8x + 7.2x^2 \text{ (meV) [4].} \quad (1)$$

$$E_{Si}(A) = 34.8 + 47.3x + 465x^{3.5} \text{ (meV) [9].} \quad (2)$$

$$E_C(A) = 26.7 + 5.56x + 110x^{3.4} \text{ (meV) [10].} \quad (3)$$

The excitonic lines were taken into account in all of these calculations too. The free exciton binding energy was evaluated by a quadratic interpolation:

$$E_X(\Gamma) = 4.1 + 5.5x + 4.4x^2 \text{ (meV) [5].} \quad (4)$$

The impurity bound exciton binding energies were described using Haynes' rule, and the above-mentioned impurity binding energies were approximated to the corresponding values in GaAs. These led to the following two relationships:

$$E_{DX} = 1.2 + 1.8x + 1.4x^2 \text{ (meV),} \quad (5)$$

for donor bound exciton DX, and

$$E_{CX} = 2.9 + 0.62x + 12x^{3.4} \text{ (meV),} \quad (6)$$

for carbon acceptor bound exciton CX, respectively.

A comparison of both the experimental and calculated results helped us to identify these lines. The A_1 and A_2 lines are related to the carbon and silicon-acceptor, respectively. The main part of the broad line is related to the free electron–neutral acceptor transitions. The highest energy edges are above the band gap energies and are related to the Fermi level in the n^+-$Al_xGa_{1-x}As$ layers. The band X in $Al_xGa_{1-x}As$ is attributed to free and donor-bound exciton transitions.

The broad band d which is visible as the lowest energy line in the $Al_xGa_{1-x}As$ spectra has lower values than the minimum energy of transitions related to shallow impurity. This broad band emission is, therefore, attributed to point defects or complexes of Si with point defects.

The PL spectra of the V1 heterostructure excited with a laser intensity of 1.36 Wcm^{-2} at temperatures varying from 3.6 K up to 300 K are presented in Figure 7. As in the case of heterostructure V2, two segments in the spectra associated with PL of GaAs and $Al_{0,2}Ga_{0,8}As$ layers can be resolved.

The weak line (arrow [BX] pointed at 1.795 eV) is related to the exciton bound to the donor emission. The luminescence efficiencies of $Al_xGa_{1-x}As$ are affected by the V/III flux ratio and the growth temperature. When the growth temperature increases above T_s = 700 ºC, the efficiency increases and sharp excitonic emission is observed. However, our investigated structures were grown at a low temperature of T_s = 600 °C and only weak excitonic PL spectra of $Al_{0.2}Ga_{0.8}As$ layers were observed. At higher temperatures the band-to-band (*b*–*b*) transitions are dominant.

PL decay times of heterostructures V1 and V2 were investigated using TCSPC technique as well.

Current-voltage characteristic of point-contact microwave diode T1 measured at room temperature is presented in Figure 8. It can be seen that the characteristic is nearly ohmic, while the theory predicts that it should be rectifying. Ohmic current-voltage cahascteristics of GaAs/AlGaAs heterojunctions were obtained by other author as well when LPE was used for the epitaxial growth of the heterojunction [11, 12]. When heterojunction is grown using LPE a graded-gap junction is obtained. Detailed analysis has showed that ohmic current-

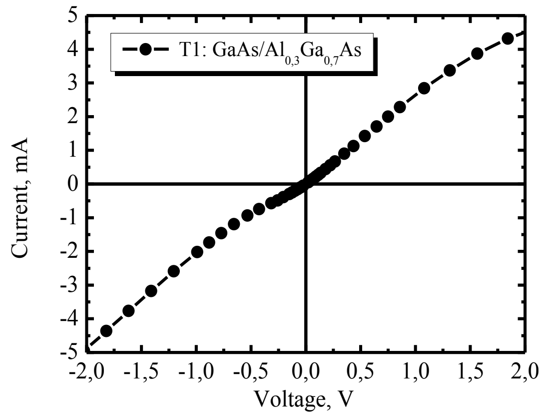


Figure 8. Current-voltage characteristic of point-contact microwave diode T1 measured at room temperature.

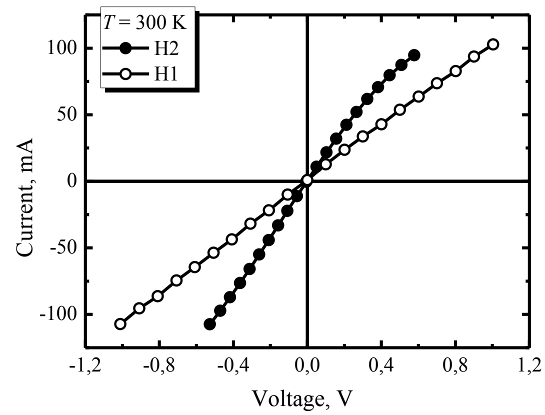
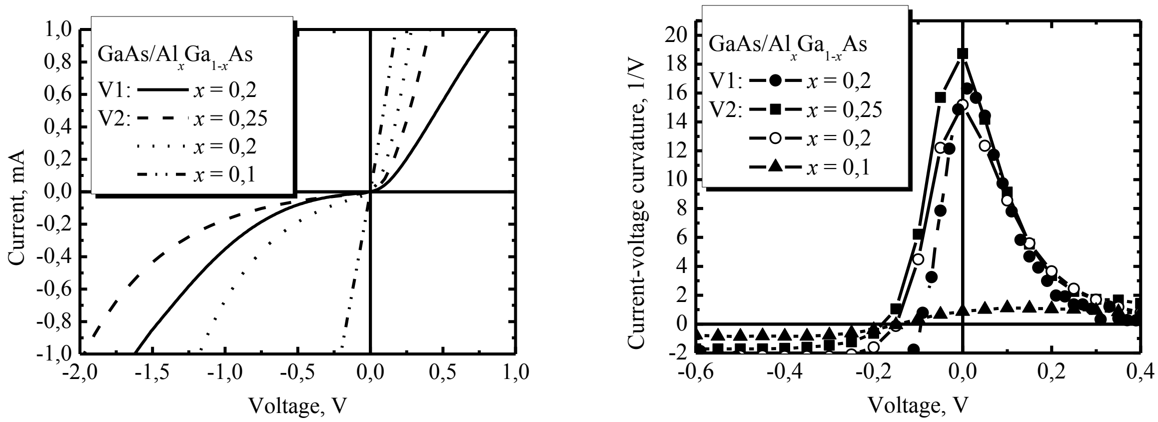


Figure 9. Current-voltage characteristic of microwave diode H1 (open circles) and H2 (solid circles) measured at room temperature.

voltage characteristics are obtained due to energy barrier lowering in the graded-gap heterojunction.

Current-voltage characteristics of asymmetrically necked microwave diodes H1 and H2 measured at room temperature are depicted in Figure 9. In order to avoid crystal lattice heating short pulses of direct current were used. Forward direction was assumed when positive potential was on the less necked part of the diode. Results showed that the differential resistance of diode H2 was smaller than that of the diode H1. Heterojunctions for H2 and H1 microwave diodes were both selectively doped, i.e. only barrier layer $Al_{0,25}Ga_{0,75}As$ was doped. The difference was in the doping profile used. Barrier layer in heterostructure H1 was doped homogeneously – donor distribution in the barrier layer was homogeneous. δ-doping was used in the case of heterostructure H2 – only very thin layer in the $Al_{0,25}Ga_{0,75}As$ layer was doped, while the rest of the layer was left undoped. As was shown earlier, electron mobility in two dimensional channel near the junction is increased as the thickness of doped layer is decreased [13]. Therefore, the differential resistance of microwave diode H2 is lower than that of the diode H1.

Current-voltage characteristics of planar rectifying microwave diodes V1 and V2 measured at room temperature are presented in Figure 10 (a). As the AlAs mole fraction x is decreased the potential barrier height in the $GaAs/Al_xGa_{1-x}As$ heterojunction is decreased as well. Therefore, the current in the reverse direction is increased and the rectification is



(a) (b)

Figure 10. Current-voltage characteristics of planar rectifying microwave diodes V1 and V2 (a) and estimated curvature coefficient dependence of applied voltage (b).

reduced. Results show that microwave diodes fabricated using GaAs/$Al_{0,1}Ga_{0,9}As$ heterojunction exhibits ohmic current-voltage characteristic at room temperature.

In order to evaluate the rectification efficiency current-voltage curvature parameter γ is used:

$$\gamma = \frac{\left(\dfrac{d^2 I}{dU^2}\right)}{\left(\dfrac{dI}{dU}\right)}, \tag{7}$$

here U – applied voltage, I – current strength through the junction.

Current-voltage curvatures as the function of applied voltage of microwave diodes V1 and V2 are presented in Figure 10 (b). It is clearly seen, that the curvature is largest when the applied voltage is 0 V, except for the microwave diode fabricated on GaAs/$Al_{0,1}Ga_{0,9}As$. In the later case the curvature coefficient is smaller and constant for the forward direction.

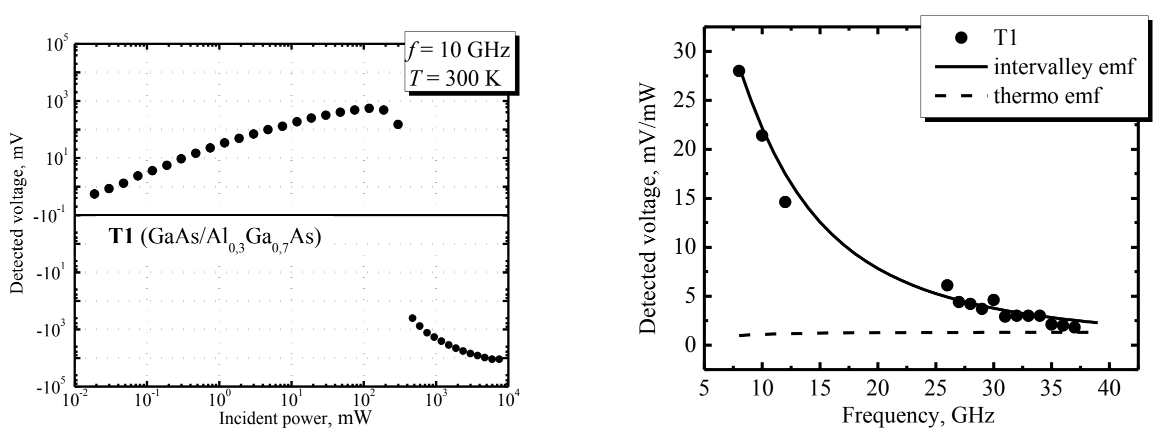
Series resistance of microwave diode V1 is larger than that of V2 fabricated using GaAs/$Al_{0,2}Ga_{0,8}As$. Ohmic contacts for microwave diodes were made using rapid thermal annealing of deposited Ni/Ge/Au metal layers. During the thermal annealing Ge penetrates into GaAs or AlGaAs for approximately 70 nm – 250 nm depending on the thickness of metal layers, annealing time and temperature [14]. In the case of microwave diode V1 upper highly doped n^+-GaAs and n^+-$Al_{0,2}Ga_{0,8}As$ layers are 50 nm thick. Therefore, it may be supposed that the upper small area metallic contact forms a low barrier Schottky junction with the lightly doped n-AlGaAs layer. This junction in series increases the resistance of microwave diode V1.

4. Investigation of detection properties of microwave diodes

The dependence of detected voltage on microwave power (voltage–power characteristics) of point contact microwave diodes T1 at 10 GHz measured at room temperature is presented in Figure 11 (a). The positive potential of the detected voltage was on the point-contact of the diode. This polarity coincides with the polarity of hot-electron thermo electromotive force in n/n^+-$Al_{0,3}Ga_{0,7}As$ homojunction, intervalley electromotive force in n/n^+-$Al_{0,3}Ga_{0,7}As$ homojunction and rectification of microwave currents in $GaAs/Al_{0,3}Ga_{0,7}As$ heterojunction.

Voltage sensitivity $S_U = 30$ mV/mW from the linear part of the heterojunction was estimated. Detected voltage is proportional to the incident microwave power up to 1 mW. Further increase of microwave power causes the detected voltage to saturate and even change the polarity of detected voltage.

In order to estimate the dominant detection mechanism in microwave diode T1 the



(a) (b)

Figure 11. Detected voltage dependence on incident microwave power of point-contact microwave diodes measured at 10 GHz (a) and voltage sensitivity dependence on microwave frequency (b) at room temperature.

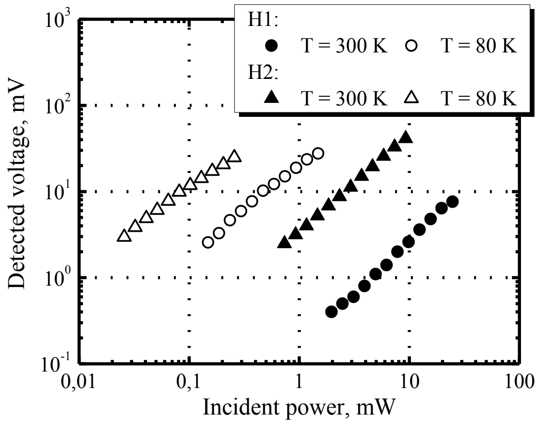


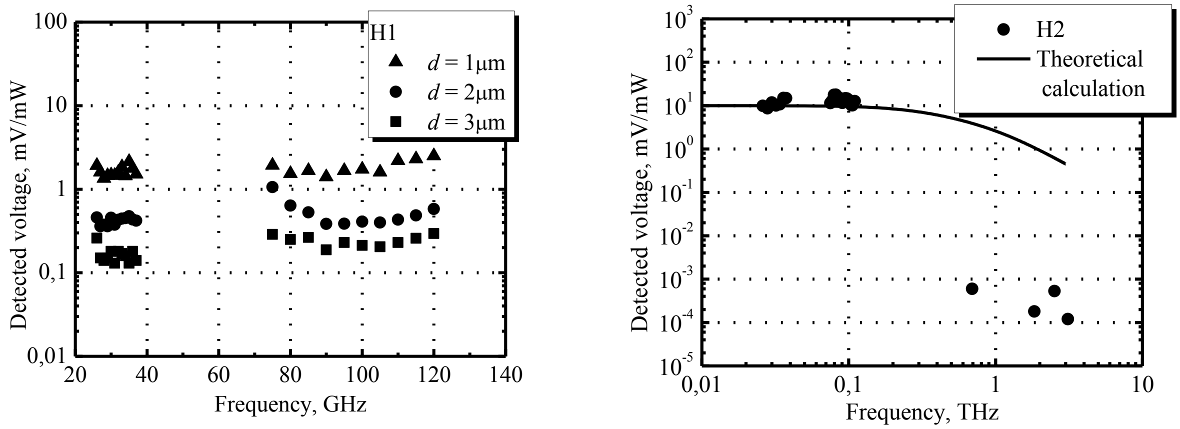
Figure 12. Dependence of detected voltage on incident microwave radiation of microwave diode H1 (circles) and H2 (triangles) measured at room and liquid nitrogen temperatures at 26 GHz.

frequency dependence of voltage sensitivity was measured in the frequency ranges 8 GHz – 12.5 GHz and 26 GHz – 37,5 GHz (Figure 11 (b)). Voltage sensitivity decreases with the frequency obeying the law of $1/\omega^2$. This dependence is inherent to the intervalley electromotive force and rectification. Therefore these mechanisms dominate in the detection of the point-contact microwave diode T1 at low frequencies. At higher frequencies the thermo electromotive force becomes considerable.

Voltage power characteristics of the planar asymmetrically necked $GaAs/Al_{0,25}Ga_{0,75}As$ diodes H1 and H2 with homogeneously and δ-doped barriers, respectively, measured at room and liquid nitrogen temperatures are shown in Figure 12. The detected voltage linearly depends on MW power for both types of the diodes at room and liquid nitrogen temperatures.

Voltage sensitivity of the diode H1 having homogeneously doped barrier is 0.3 V/W at room temperature and increases to about 20 V/W value at liquid nitrogen temperature. Microwave diode H2 having δ-doped barrier layer demonstrates voltage sensitivity of 2 V/W at room temperature and up to 120 V/W at liquid nitrogen temperature. Higher sensitivity of both diodes at liquid nitrogen temperature is caused by higher values of electron mobility and electron energy relaxation time. Microwave diode H2 on the base of $GaAs/Al_{0,25}Ga_{0,75}As$ heterostructures with δ-doped barrier layer have higher sensitivity due to higher electron mobility because the thickness of the doped layer is decreased [13].

Frequency dependences of the voltage sensitivity of microwave diodes H1 having different width of the narrowest part of the diode are depicted in Figure 13 (a). Voltage sensitivity increases from 0.2 V/W up to 2 V/W as the narrowest part of the planar diode is



(a) (b)

Figure 13. Detected voltage dependence on microwave frequency of microwave diodes H1 having different widths of the necked part (a) and detected voltage dependence on microwave frequency of microwave diode H2 (b).

narrowed from 3 μm down to 1 μm. Experimentally obtained voltage sensitivity does not change in the 26 GHz to 120 GHz frequency range.

Voltage sensitivity values from GHz up to THz frequencies of microwave diode H2 with δ-doped barrier are depicted in Figure 13 (b). Calculation shows that sensitivity of the planar diode should not change with frequency up to 60 GHz and should begin to decrease at higher frequencies. When $\omega\tau >> 1$ (τ is electron pulse relaxation time), the sensitivity decreases with ω according to ω^{-2}. However, experiment shows that sensitivity is nearly constant in microwave frequency range (25 GHz – 120 GHz) but at THz frequencies (0.7 THz – 3 THz) it decreases more rapidly than theory predicts. We associate this decrease with significant change of absorbed power by the diode.

Voltage-power characteristic of planar rectifying microwave diode V1 measured at 26 GHz at room temperature is presented in Figure 14 (a). Estimated square law region of the detected voltage is up to 20 μW. With further increase of incident microwave power detected voltage begins to saturate. Voltage sensitivity of microwave diodes V1 at 26 GHz is 1440 mV/mW. Voltage-power characteristics of microwave diodes V1 having different active region cross-section are presented in Figure 14 (b). It is clearly seen that increasing

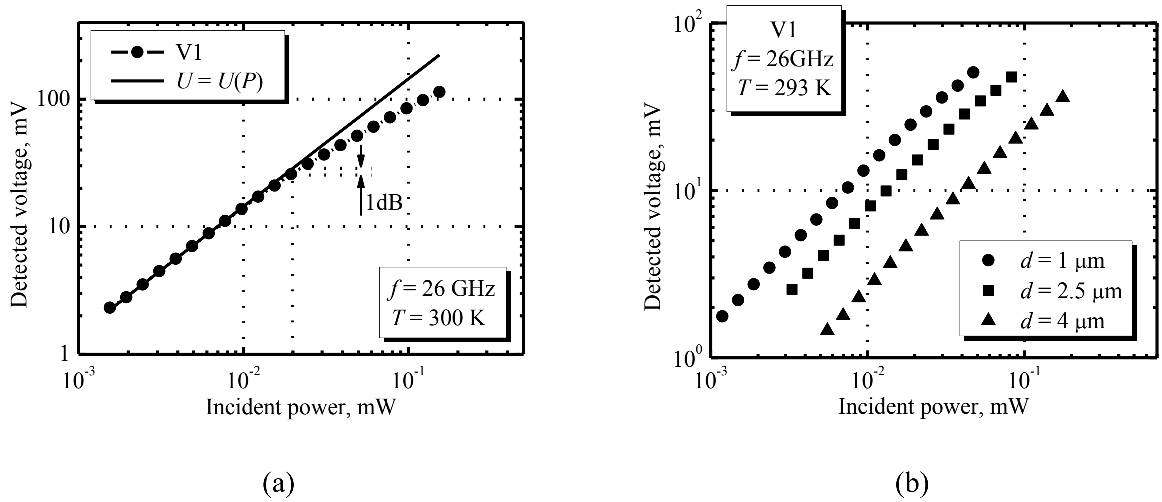


Figure 14. Voltage-power characteristic of planar rectifying microwave diodes V1 measured (a) and voltage-power characteristics of diodes V1 having different cross-section areas of active region (b) measured at 26 GHz at room temperature.

the cross-section of active region significantly decreases the voltage sensitivity. This is attributed to the increase of the junction capacitance.

Voltage power characteristics of planar rectifying microwave diodes V2 having different AlAs mole fraction x measured at 26 GHz at room temperature are presented in Figure 15 (a). Diodes with AlAs mole fraction $x = 0{,}1$ had the smallest voltage sensitivity as was predicted from current-voltage characteristic. However, diodes with $x = 0{,}2$ had slightly larger voltage sensitivity than those with $x = 0{,}25$. At low frequencies voltage sensitivity is proportional to current-voltage curvature and does not depend on frequency. However, at larger frequencies voltage sensitivity starts to depend on junction resistance and capacitance. Increasing AlAs mole fraction x causes the increase of junction resistance, therefore the voltage sensitivity of the diodes V2 with $x = 0{,}25$ is smaller than that of the diode with $x = 0{,}2$.

Voltage sensitivity dependence on microwave frequency of planar rectifying microwave diodes V2, having different AlAs mole fraction x are presented in Figure 15 (b). In the investigated frequency range voltage sensitivity of diodes with $x = 0{,}25$ and $x = 0{,}2$ decreases with the $1/\omega^2$. This is inherent to the rectification mechanism of detection.

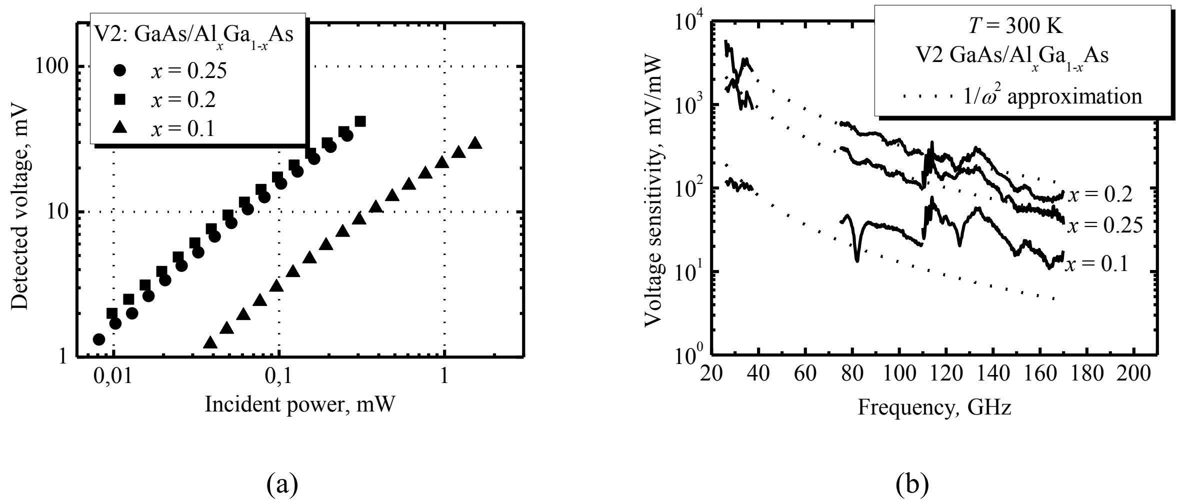


Figure 15. Voltage-power characteristic measured at 26 GHz (a) and voltage sensitivity dependence on microwave frequency (b) of planar rectifying microwave diodes V2, having different AlAs mole fraction x.

However, voltage sensitivity decrease of the diode with $x = 0{,}1$ is slightly slower, indicating higher cut-off frequency.

Results and conclusions

- Experimental investigation of photoluminescence in GaAs/$Al_xGa_{1-x}As$ heterostructures have shown, that quality of epitaxial structures grown by molecular beam epitaxy depends on growth temperature. Higher quality of GaAs was obtained in the heterostructures grown at 600 °C, while higher quality of $Al_xGa_{1-x}As$ was obtained in the heterostrucutres grown at 700 °C temperature.
- Current-voltage characteristic of point-contact GaAs/$Al_xGa_{1-x}As$ microwave diode grown by liquid phase epitaxy was nearly ohmic at room temperature due to the graded heterojunction.
- Planar asymmetrically necked GaAs/$Al_{0,25}Ga_{0,75}As$ microwave diodes with δ-doped barrier layer has the lower differential resistance than planar asymmetrically necked GaAs/$Al_{0,25}Ga_{0,75}As$ microwave diodes with homogeneously doped barrier layer due to higher electron mobility.
- Detection of microwaves in point contact GaAs/$Al_{0,3}Ga_{0,7}As$ microwave diode is mainly due to the rectification in heterojunction and intervalley electromotive force in n/n^+-$Al_{0,3}Ga_{0,7}As$ homojunction.
- Planar asymmetrically necked GaAs/$Al_{0,25}Ga_{0,75}As$ microwave diodes with δ-doped barrier layer has the larger voltage sensitivity than planar asymmetrically necked GaAs/$Al_{0,25}Ga_{0,75}As$ microwave diodes with homogeneously doped barrier layer due to higher electron mobility.
- Voltage sensitivity of planar GaAs/$Al_xGa_{1-x}As$ microwave diodes depends on AlAs mole fraction x. Largest voltage sensitivity was obtained with diodes having AlAs mole fraction $x = 0,2$.

References

[1] H. C. Torrey, C. A. Whitmer, and S. A. Goudsmit, *Crystal Rectifiers*: McGraw-Hill Book Company, 1948.

[2] D. T. Young and J. C. Irvin, "Millimeter frequency conversion using Au-n-type GaAs Schottky barrier epitaxial diodes with a novel contacting technique," *Proceedings of the IEEE,* vol. 53, pp. 2130-2131, 1965.

[3] R. I. Harrison and J. E. Zucker, "Hot-carrier microwave detector," *Proceedings of the IEEE,* vol. 54, pp. 588-595, 1966.

[4] L. Pavesi and M. Guzzi, "Photoluminescence of AlxGa1-xAs alloys," *Journal of Applied Physics,* vol. 75, p. 4779, 1994.

[5] C. Bosio, J. L. Staehli, M. Guzzi, G. Burri, and R. A. Logan, "Direct-energy-gap dependence on Al concentration in $Al_xGa_{1-x}As$," *Physical Review B,* vol. 38, pp. 3263-3268, 1988.

[6] G. D. Gilliland, D. J. Wolford, T. F. Kuech, and J. A. Bradley, "Luminescence kinetics of intrinsic excitonic states quantum-mechanically bound near high-quality (n^--type GaAs)/(p-type $Al_xGa_{1-x}As$) heterointerfaces," *Physical Review B,* vol. 49, pp. 8113-8125, 1994.

[7] J. X. Shen, Y. Oka, W. Ossau, G. Landwehr, K. J. Friedland, R. Hey, K. Ploog, and G. Weimann, "Vertical transport of photo-excited carriers for excitonic recombinations in modulation doped $GaAsGa_{1-x}Al_xAs$ heterojunctions," *Solid State Communications,* vol. 106, pp. 495-499, 1998.

[8] H. Kunzel and K. Ploog, "The effect of As_2 and As_4 molecular beam species on photoluminescence of molecular beam epitaxially grown GaAs," *Applied Physics Letters,* vol. 37, pp. 416-418, 1980.

[9] G. Oelgart, G. Lippold, M. Proctor, D. Martin, and F. K. Reinhart, "Ionization energy of the Si acceptor on $Al_xGa_{1-x}As$," *Semiconductor science and technology,* vol. 6, p. 1120, 1991.

[10] R. Heilman and G. Oelgart, "Ionization energy of the carbon acceptor in $Al_xGa_{1-x}As$," *Semiconductor science and technology,* vol. 5, p. 1040, 1990.

[11] J. F. Womac and R. H. Rediker, "The graded-gap $Al_xGa_{1-x}As$-GaAs heterojunction," *Journal of Applied Physics,* vol. 43, pp. 4129-4133, 1972.

[12] S. C. Lee and G. L. Pearson, "Rectification in $Al_xGa_{1-x}As$-GaAs N-n heterojunction devices," *Solid-State Electronics,* vol. 24, pp. 563-568, 1981.

[13] E. F. Schubert, L. Pfeiffer, K. W. West, and A. Izabelle, "Dopant distribution for maximum carrier mobility in selectively doped $Al_{0.30}Ga_{0.70}As$/GaAs heterostructures," *Applied Physics Letters,* vol. 54, pp. 1350-1352, 1989.

[14] Y.-C. Shih, M. Murakami, E. L. Wilkie, and A. C. Callegari, "Effects of interfacial microstructure on uniformity and thermal stability of AuNiGe ohmic contact to n-type GaAs," *Journal of Applied Physics,* vol. 62, p. 582, 1987.

List of publications related to thesis:

[P1] S. Ašmontas, V. Kazlauskaitė (Nargelienė), A. Sužiedėlis, J. Gradauskas, E. Širmulis, and V. Derkach, „Detectors of microwave and terahertz radiation on the basis of semiconductor nanostructures“, *European Microwave Conference, proceedings*, 1650-1653 (2009).

[P2] A. Sužiedėlis, S. Ašmontas, V. Kazlauskaitė (Nargelienė), J. Gradauskas, „Sensitivity increase of point contact hot carrier microwave detector“ *Electronics letters*, **45**, 25, 1328-1329 (2009).

[P3] A. J. Kundrotas, A. Čerškus, V. Nargelienė, A. Sužiedėlis, S. Ašmontas, J. Gradauskas, A. Johannessen, E. Johannessen, V. Umansky, „Enhanced exciton photoluminescence in the selectively Si-doped GaAs/AlxGa1–xAs heterostructures“, *Journal of applied physics*, **108**, 6, 063522-1-7 (2010).

[P4] J. Gradauskas, A. Sužiedėlis, S. Ašmontas, E. Širmulis, V. Kazlauskaitė (Nargelienė), A. Lučun, M. Vingelis, „Sensitive planar heterojunction detector from microwave to infrared applications“, *IEEE Sensors journal*, **10**, 3, 662-667 (2010).

[P5] A. Čerškus, A. J. Kundrotas, V. Nargelienė, A. Sužiedėlis, S. Ašmontas, J. Gradauskas, A. Johannessen, E. Johannessen, „Photoluminescence characterisation of GaAs/AlGaAs structures designed for microwave and terahertz detectors“, *Lithuanian Journal of Physics*, **51**, 4, 330-334 (2011).

[P6] A. Sužiedėlis, S. Ašmontas, A. J. Kundrotas, J. Gradauskas, A. Čerškus, V. Nargelienė, T. Anbinderis, „Planar heterojunction diode for millimeter waves detection“, *PIERS proceedings*, 927-930 (2012).

[P7] A. Suziedelis, S. Asmontas, J. Kundrotas, V. Nargeliene, and J. Gradauskas, "Voltage sensitivity of a point-contact GaAs/AlGaAs heterojunction microwave detector," *Physica Scripta,* **85**, 3, 035702 (2012).

[P8] A. Čerškus, A. J. Kundrotas, V. Nargelienė, A. Sužiedėlis, S. Ašmontas, J. Gradauskas, A. Johannessen, E. Johannessen, „Dynamic photoluminescence studies of vertical n^+/n-GaAs/$Al_{0.2}Ga_{0.8}As$ structures designed for microwave electronics“, *Physica scripta*, **87**, 6, 065701-1-5 (2013).

[P9] A. Čerškus, A. J. Kundrotas, V. Nargelienė, A. Sužiedėlis, S. Ašmontas, J. Gradauskas, E. Johannessen, A. Johannessen, „Photoluminescence lifetimes in GaAs/$Al_{0.3}Ga_{0.7}As$ structures designed for microwave and terahertz detectors“ *Lithuanian journal of physics*, 53, 2, 118-125 (2013).

Conference contributions:

[K1] J. Gradauskas, A. Sužiedėlis, S. Ašmontas, E. Širmulis, V. Kazlauskaitė, A. Lučun, M. Vingelis, „Sensitive planar heterojunction detector from microwave to infrared applications",*International Symposium on Spectral Sensing Research (ISSSR 2008)*, June 23–27, 2008, Hoboken, NY, USA.

[K2] V. Kazlauskaitė, A. Sužiedėlis, A. Čerškus, J. Gradauskas, S. Ašmontas, J. Kundrotas, „Eksitoninės fotoliuminescencijos stiprinimas siliciu legiruotuose n+/i-GaAs dariniuose", *Lietuvos nacionalinė fizikos konferencija (LNFK'38)*, Birželio 8–10 d., 2009, Vilnius, Lietuva.

[K3] Ašmontas, S.; Kazlauskaitė, V.; Sužiedėlis, A.; Gradauskas, J.; Širmulis, E.; Derkach, V.; Detectors of microwave and terahertz radiation on the basis of semiconductor nanostructures, *39th European Microwave Conference,* September 28–October 1, 2009, Rome, Italy.

[K4] A. Sužiedėlis, S. Ašmontas, J. Požela, J. Gradauskas, V. Nargelienė, Č. Paškevič, V. Derkach, R. Golovashchenko, E. Goroshko, V. Korzh, T. Anbinderis, „Magnetic field influence on properties of planar microwave diodes on the base of modulation doped semiconductor structures", *20th Internatonal Crimean Conference on Microwave & Telecommunication Technology (CriMiCo)*, September 13–17, 2010, Sevastopol, Ukraine.

[K5] A. Čerškus, J. Kundrotas, V. Nargelienė, A. Sužiedėlis, S. Ašmontas, J. Gradauskas, A. Johannessen, E. Johannessen, „Photoluminescence characterisation of GaAs/AlGaAs structures designed for microwave and terahertz detectors", *International Conference on Advanced Optical Materials and Devices (AOMD-7)*, August 28–31, 2011, Vilnius, Lithuania.

[K6] J. Kundrotas, A. Čerškus, V. Nargelienė, A. Sužiedėlis, S. Ašmontas, J. Gradauskas, A. Johannessen, E. Johannessen, „Enhanced exciton photoluminescence in the Si-doped GaAs/AlxGa1–xAs homo- and heterojunctions", *International Conference on Advanced Optical Materials and Devices (AOMD-7)*, August 28–31, 2011, Vilnius, Lithuania.

[K7] A. Sužiedėlis, S. Ašmontas, J. Kundrotas, J. Gradauskas, E. Širmulis, A. Čerškus, V. Nargelienė, „Planar heterojunction diodes for microwave and infrared applications", *International Conference on Advanced Optical Materials and Devices (AOMD-7)*, August 28–31, 2011, Vilnius, Lithuania.

[K8] A. Sužiedėlis, S. Ašmontas, A. J. Kundrotas, J. Gradauskas, A. Čerškus, V. Nargelienė, T. Anbinderis, „Planar heterojunction diode for millimeter waves detection", *Progress in Electromagnetics Research Symposium (PIERS 2012)*, August 19–23, 2012, Moscow, Russia.

[K9] A. Čerškus, V. Nargelienė, A. Sužiedėlis, S. Ašmontas, J. Gradauskas, B. Kundrotas, R. Rinkevičienė, „Time-resolved photoluminescence characterisation of $GaAs/Al_xGa_{1-x}As$ structures designed for microwave and terahertz detectors“, *15th International Symposium on Ultrafast Phenomena in Semiconductors (15 UFPS)*, August 25–28, 2013, Vilnius, Lithuania.

[K10] J. Kundrotas, A. Čerškus, V. Nargelienė, A. Sužiedėlis, S. Ašmontas, J. Gradauskas, E. Johannessen, A. Johannessen, „The increase of radiative lifetime of free excitons in selectively Si-doped $GaAs/Al_xGa_{1-x}As$ heterostructures“, *15th International Symposium on Ultrafast Phenomena in Semiconductors (15 UFPS)*, August 25–28, 2013, Vilnius, Lithuania.

Reziumė

Pagrindinis disertacijos tikslas – sukurti mikrobangų diodus įvairiatarpių $GaAs/Al_xGa_{1-x}As$ puslaidininkinių darinių pagrindu ir ištirti jų detekcines savybes elektromagnetinės spinduliuotės milimetrinių bangų ilgių ruože.

Disertacija yra sudaryta iš keturių skyrių, suskirstytų į smulkesnius poskyrius.

Pirmasis skyrius yra skirtas apžvelgti mikrobangų detekcijos metodus ir kitų mokslinių grupių atliktus detektorinių diodų tyrimus. Šiame skyriuje taip pat yra aprašomas įvairiatarpių darinių energijos juostų modelis ir krūvininkų pernaša statmenai bei lygiagrečiai įvairiatarpiam barjerui, bei disertacijoje nagrinėjamų diodų mikrobangų detekcijos mechanizmai.

Antrasis skyrius yra skirtas įvairiatarpių $GaAs/Al_xGa_{1-x}As$ darinių sandaros, bei auginimo metodų aprašymui. Šiame skyriuje taip pat yra aprašomi mikrobangų gamybos technologiniai procesai.

Trečiasis skyrius yra skirtas aprašyti $GaAs/Al_xGa_{1-x}As$ darinių tyrimus optiniais bei elektriniais metodais. Puslaidininkinių sluoksnių kokybė buvo įvertinta naudojant nuostoviosios fotoliuminescencijos ir laike koreliuotų fotonų skaičiavimo metodus. Pagamintų diodų elektrinėms savybėms įvertinti buvo išmatuotos jų voltamperinės charakteristikos.

Ketvirtasis skyrius skirtas mikrobangų diodų detekcinių savybių plačiame mikrobangų dažnių ruože nuo 8 GHz iki 170 GHz tyrimų rezultatų aptarimui. Aprašomi įvairiatarpių $GaAs/Al_xGa_{1-x}As$ taškinių ir planarinių mikrobangų diodų, bei nesimetriškai susiaurintų $GaAs/Al_{0,25}Ga_{0,75}As$ planarinių mikrobangų diodų detektuotos įtampos ir jautrio matavimų rezultatai.

About the author

Name and surname:	Viktorija Nargelienė	
Birth date and place:	August 1, 1984, Vilnius, Lithuania	
E-mail:	vika@pfi.lt	
Education:	2002	Secondary education, Vilniaus Mykolo Biržiškos gymnasium
	2006	Bachelor Degree in Physics of telecommunications and electronics, Vilnius University
	2008	Master degree in Physics, Vilnius University
	2008-2012	Doctoral studies at Center for Physical Sciences and Technology and Vilnius University
Scientific experience:	2006 - 2006	Technician, Semiconductor Physics Institute
	2006 – 2008	Engineer, Semiconductor Physics Institute
	2008 – till now	Junior scientific researcher, Center for Physical Sciences and Technology
Publications:	Co-author of 20 publications and 10 presentations in scientific conferences	

Apie autorę

Vardas Pavardė:	Viktorija Nargelienė	
Gimimo data ir vieta:	1984 m. rugpjūčio 1 d., Vilnius, Lietuva	
El. paštas:	vika@pfi.lt	
Išsilavinimas:	2002	Vidurinis išsilavinimas, Vilniaus Mykolo Biržiškos gimnazija
	2006	Telekomunikacijų fizikos ir elektronikos bakalauro diplomas, Vilniaus Universitetas
	2008	Fizikos magistro diplomas, Vilniaus Universitetas
	2008-2012	Doktorantūros studijos, Fizinių ir technologijos mokslų centras
Profesinė patirtis:	2006 - 2006	Laborantė, Puslaidininkių fizikos institutas
	2006 – 2008	Inžinierė, Puslaidininkių fizikos institutas
	2008 – iki dabar	Jaunesnioji mokslo darbuotoja, Fizinių ir technologijos mokslų centras
Publikacijos:	20 mokslinių publikacijų ir 10 pranešimų mokslinėse konferencijose bendraautorė	