VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
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INVESTIGATION OF $A^{III}B^{V}$ HETEROSTRUCTURES UNDER THE ACTION OF MICROWAVE RADIATION

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS
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General characteristic of the dissertation

Topicality and problem of the work. Modern development of semiconductor electronics is mostly determined by the fundamental research in the field of semiconductor physics. The investigation of the characteristics of semiconductors in the strong electric fields within the range of electromagnetic microwave radiation takes up a significant place. The major trend for development of modern electronics is nanoelectronics, which is going to substitute in the nearest future the traditional microelectronics. While reclusing the dimensions of semiconductor elements and investigating the physical processes in them under the influence of electromagnetic radiation, there tend to appear new phenomena and after having carried the research on them, it becomes possible to design new devices or perfect the already known ones. Meanwhile, as the electronic systems have a tendency to be extensively developed, the interest has been particularly paid onto the systems of detection of electromagnetic radiation.

The semiconductor (Si, Ge) electromagnetic radiation sensors developed so far do not exhibit high sensitivity. After having applied heterostructure modulations it is possible to perfect the sensitivity of the samples, due to the fact that heating of the carriers in semiconductors is directly proportional to the sensitivity. In the heterostructure junction established two-dimensional channel of electrons (2DE) allows to achieve extremely high values of the carrier mobility, therefore it is possible to increase the sensitivity of such type of sensors. When reducing the dimensions of the sensors it is also possible to increase the sensitivity of the sensors, but the resistance of the sensors increases as well. That is why one proposed method in solving the problem is to use semiconductor materials with high mobility of carriers. The previously mentioned types of sensitive diodes of hot carriers are usually used to detect signals of low power electromagnetic radiation. It is very important for these sensors to detect directly electromagnetic radiation without the bias of external voltage. This significantly simplifies the design of the microwave devices of electromagnetic radiation, increases their reliability, reduces their cost and thus they tend to be universal in their application.

The aim of the work. To increase the sensitivity of the narrowed sensors of radiation as well as to determine the influence of the sample structure on to the detected signal and its magnitude.

Tasks of the work

1. To investigate the influence of microwave radiation on the narrowed semiconductor structures and determine the physical nature of the observed effects.
2. To analyze the characteristics of the narrowed heterostructure semiconductor samples depending on the quality of the layers of the structures and on the parameters of semiconductor materials.
3. To investigate the characteristics of the microwave sensors depending on the conductivity of the highly doping semiconductor layer of the selectively doped sample, on the thickness of the dividing layer and on the type of metallization of the gate.
4. To evaluate the possibility of practical implementation of the AlGaAs/GaAs, AlGaAs/InGaAs/GaAs and GaAs structures in producing of microwave radiation sensors.

Scientific novelty

1. There have been investigated for the first time the characteristics of the narrowed selectively doped AlGaAs/GaAs heterostructures having different thickness of separating layers, with the buffer layer of the superlattice, with applied gate type of metallization, and characteristic of pseudomorphic AlGaAs/InGaAs/GaAs formation under the action of microwave field.
2. There has been shown that there appears the electromotive force across the narrowed heterostructures under the influence of microwave radiation; the character and quantitative parameters of it depend on the quality of the layers of the structures, on the parameters of semiconductor materials and on microwave frequency.
3. The design of the microwave sensor of sub-micrometric dimensions with symmetrically and asymmetrically narrowed structures to detect microwaves has been proposed.

Research methods. Microwave measurements were performed using pulse modulated magnetron generator operating at $f = 10$ GHz frequency and klystron generator in K_a (26÷37.5) GHz frequency range. Photoluminescence experiments were performed under illumination of Ar ion laser (quantum energy of about 2.5 eV). The excitation intensity was varied from 0.2 up to 30 W/cm^2.

Practical value. The obtained results may be used to design sensors of microwave radiation that detect directly electromagnetic radiation without any external voltage bios.

Defended propositions

1. There has been experimentally determined that the voltage sensitivity of symmetrically and asymmetrically narrowed microwave diodes depends on the width of the neck of the structure and increases when using semiconductor materials with high carrier mobility.
2. The insertion of additional non-doped InGaAs layer between the separating i-AlGaAs layer and non-doped i-GaAs layer in the microwave diodes of narrowed selectively doped AlGaAs/GaAs structures, without violating the critical InGaAs layer thickness, increases the voltage sensitivity of the sensors both in liquid nitrogen and in room temperatures.
3. When using gate type metallization above the active layer in the microwave diodes of asymmetrically narrowed selectively doped AlGaAs/GaAs structures, it is possible to increase significantly the voltage sensitivity of the diodes both in room and liquid nitrogen temperatures.

Approval of the results. 10 scientific publications have been manifested on the subject of the dissertation, 6 of them in the journals with Thomson ISI Web of Science citation index, 1 paper in the journal with ISI Master Journal List citation index, 3 papers in the revised materials of presentations if the international conference referred in ISI Proceedings database. The results of dissertation have been discussed of 7 international, 1 foreign and 2 national conferences. 3 papers brave been published in the collections of conference presentations.

The scope of the scientific work. The scientific work consists of the general characteristic of the dissertation, 3 main chapters, conclusions, list of literature, and list of publications. The total scope of the dissertation – 102 pages, 55 pictures.

The content of the dissertation

Introduction motivates the analysed problem and the topicality of the work, the main aim of the work, the solved problems, scientific novelty, practical value and the statements to be defended are indicated here.

1. Heavily doped n-GaAs diode

A detector of electromagnetic radiation can operate on free carrier heating effects in non-uniform semiconductor structures. Voltage sensitivity of the detector depends on the size of the neck of the diode: reducing the width of the neck results in a higher value of the sensitivity, however, the electrical resistance of the diode increases at the same time, thus leading to the decrease of both operational speed and amount of absorbed microwave power which in turn, reduces the voltage sensitivity of the diode. The electrical resistance of the detector can be lowered by higher doping of the semiconductor layer.

Molecular beam epitaxy grown structures (see Fig 1) were used for the fabrication of microwave diodes of two different configurations: asymmetrically shaped diodes (AD) and microwave diodes with symmetrically necked semiconductor layer (SD). The height of the MBE grown n^+-GaAs layer was h = 100 nm, while, the width d of the neck of the diodes varied from 1 μm up to 3 μm. Donor density in the n^+-GaAs layer was $N_d = 1 \cdot 10^{18}$ cm^{-3}. Hall measurements gave the value of electron mobility in the epitaxial layer $\mu = 3000$ $cm^2V^{-1}s^{-1}$.

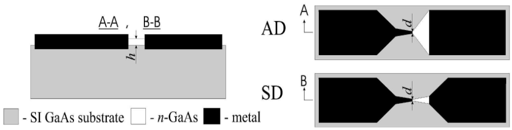


Fig 1. Schematic view of asymmetrically (AD) and symmetrically (SD) shaped microwave diodes

Testing of the planar microwave diodes in DC regime showed linear current-voltage characteristics, as well as correspondence of the electrical resistance value to their geometry. The polarity of the detected voltage in microwaves corresponded to that of thermoelectric effect of hot carrier in n-n^+ junction. Dependences of the detected voltage on microwave power of the symmetrical diodes are presented in Fig 2a. Higher values of voltage sensitivity have the diodes with narrower neck of the structure. This confirms our theoretical estimations concerning the reciprocal dependence of the voltage sensitivity on the width of the neck. However, the supper-linearity of the voltage-power characteristic was observed at a higher microwave power. We

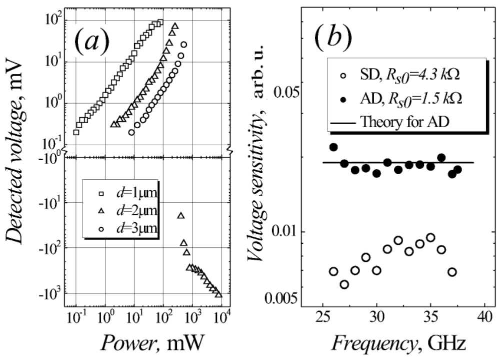


Fig 2. Voltage-power characteristics of symmetrically shaped microwave diodes with different widths of the neck (a) and frequency dependence of the asymmetrical and symmetrical microwave diodes in K_a frequency range (b)

associate this supper-linear voltage-power characteristic with the rise of intervalley electromotive force in GaAs as well as with increase of the electron energy relaxation time at room temperature in GaAs. It is about non-monotonic character of the voltage-power characteristic: increase of the microwave power caused a sudden decrease of the detected voltage followed by the change of its polarity. We explain this phenomenon with the origination of negative differential resistance in n-GaAs layer due to the Gunn effect.

Experimental frequency dependences of the voltage sensitivity of the SD and AD with the width of the neck $d = 3$ μm are presented in Fig 2b. Higher voltage sensitivity of the AD can be explained by a greater amount of absorbed microwave power due to their lower electrical resistance. One more reason for higher sensitivity of the AD lies in additional input of bigradient electromotive force (emf) of the asymmetrically shaped semiconductor structure to the detected voltage, because in case of heavily doped semiconductor the polarities of thermoelectric and bigradient emfs have the same sign. It is worth to note the weak frequency dependence of the voltage sensitivity of both types of the diodes in the investigated frequency range. Solid line in Fig 2b depicts theoretical frequency dependence of the voltage sensitivity of the microwave diode with asymmetrically shaped epitaxial layer. Thermoelectric electromotive force arises in heavily doped semiconductor structures which evidences the carrier heating phenomenon in degenerate semiconductor. The voltage sensitivity of the necked semiconductor structure increases with narrowing the neck of the diode.

2. Modulation-doped AlGaAs/GaAs structures with different spacer

The main shortcoming of the hot carrier microwave diodes is their poor voltage sensitivity. Reduction of the „neck“ dimensions of the asymmetrically shaped semiconductor structure down to submicrometric scale as well as use of 2D electron gas (2DEG) structures increased substantially voltage sensitivity of such microwave diodes, particularly at liquid nitrogen temperature. Quality of the 2DEG layer determines the detective properties of the asymmetrically shaped microwave diodes. It was shown that there exists an optimal width of the undoped i-AlGaAs spacer separating the doped n^+-AlGaAs layer from i-GaAs region where the 2DEG is formed. Hall measurements revealed the sheet electron density to be $6.2 \cdot 10^{11}$ cm^{-2} for the structure with $d_i = 75$ Å and $1.4 \cdot 10^{12}$ cm^{-2} for the structure with wider spacer ($d_i = 450$ Å) at room temperature. At liquid nitrogen temperature the electron density slightly decreased ($3.9 \cdot 10^{11}$ cm^{-2}) in the case of the structure with the narrow spacer (NS), while in case of the structure with wider spacer (WS) more significant reduction of the electron sheet concentration ($1.6 \cdot 10^{11}$ cm^{-2}) was observed.

Modulation doped AlGaAs/GaAs heterostructures were grown by MBE technique on semi-insulating GaAs substrate with different spacer width. Cross sections of the structures are depicted schematically in Fig 3a, b.

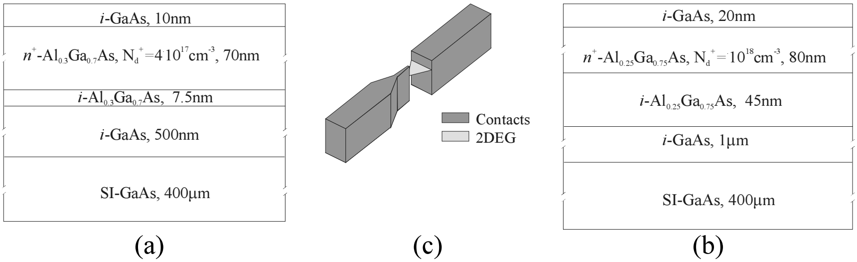
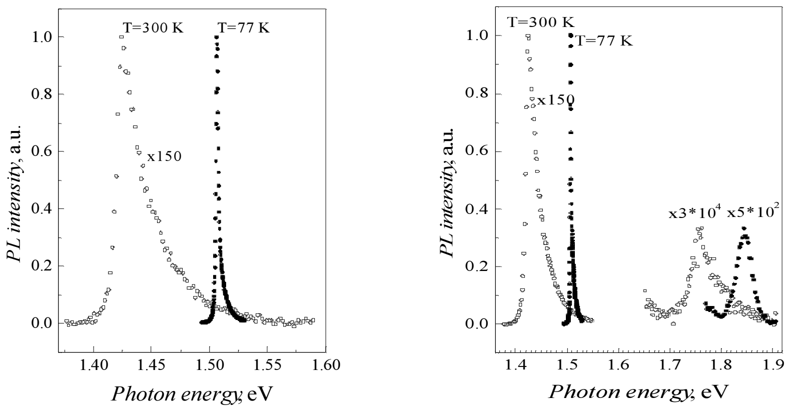


Fig 3. Cross-sections of modulation-doped GaAs/AlGaAs heterojunctions with different spacer width (a) d_i = 75 A; (b) d_i = 450 A; (c) schematic view of the microwave diode with triangularly shaped 2DEG layer

Electron mobility increased with cooling from room down to liquid nitrogen temperature for the structure with NS (μ(300 K) = 4800 $cm^2V^{-1}s^{-1}$ and μ(77 K) = 52 000 $cm^2V^1s^{-1}$), as well as for the structure with the WS (μ(300 K) = 2400 $cm^2V^{-1}s^{-1}$ and μ(77 K) = 66 000 $cm^2V^{-1}s^{-1}$). The width of the narrowest part, or the neck, of the constricted structure was taken d = (1÷3) µm. Schematic view of the planar microwave diode is shown in Fig 3c. The experimental values of electrical resistance of the WS microwave diodes corresponded to the values calculated from geometry of the semiconductor structures both at room and liquid nitrogen temperatures. The measured values of the resistance of the NS microwave diodes were higher than would follow geometry of the samples.

Photoluminescence spectra of the modulation doped GaAs/AlGaAs structures at T = 77 K and T = 300 K for both kinds of the microwave diodes are presented in Fig 4a and Fig 4b, respectively. Investigation of photoluminescence spectra of the modulation doped semiconductor structures revealed effective electron gathering into 2DEG channel from the doped AlGaAs layer of the structure with narrow spacer, while in case of wide spacer a part of charge carriers remained in the doped AlGaAs layer.

Polarity of the detected voltage on the WS microwave diode corresponded to the polarity of thermoelectric electromotive force of hot carriers for this configuration of the asymmetrically shaped microwave diode. Dependences of the detected voltage on microwave power are presented in Fig 5. Linear voltage power characteristic was observed at low microwave power level, while non-monotonic character of the dependence occurred at higher microwave power. We relate it with carrier intervalley scattering processes occurring in many-valley semiconductors.



(a) (b)

Fig 4. Photoluminescence spectra of the selectively-doped GaAs/AlGaAs structures with narrow (a) and wide (b) spacer

Voltage sensitivity of the WS microwave diodes in low microwave power region was 0.3 V/W at room temperature and 5.5 V/W at liquid nitrogen temperature. Polarity of the detected voltage of the NS microwave diodes was opposite to the detected voltage of the WS diodes.

Polarity of the voltage detected on the microwave diodes with wide spacer corresponded to the polarity of the thermoelectric electromotive force of such configuration of n-n^+

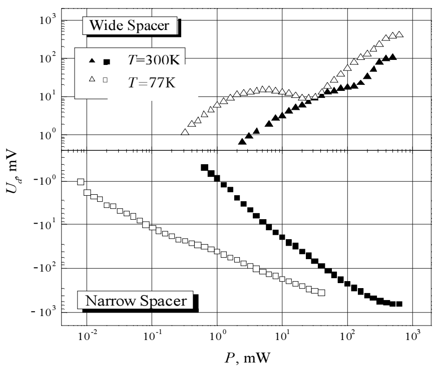


Fig 5. Voltage power characteristics of microwave diodes with narrow and wide spacer measured at room and liquid nitrogen temperatures

junction, and was opposite to the voltage polarity on the diodes with narrow spacer. The voltage sensitivity of the microwave diodes with narrow spacer was by one order higher than that of the diodes with wide spacer at room temperature, and almost by two orders higher at liquid nitrogen temperature. Effective electron gathering into 2DEG channel creates situation when an interchange between n^+ and n regions of the planar diode occurs: the configured 2DEG channel can be treated as the n^+ region, while the alloyed metallic contacts are as n region of the semiconductor structure. This consideration explains opposite polarities of the voltages detected on the microwave diodes with narrow and wide spacer.

3. Modulation-doped AlGaAs/GaAs structures with and without superlattice buffer

Present the results of investigation of microwave detection properties of asymmetrically constricted 2DEG layers fabricated on the base of modulation doped GaAs/AlGaAs and having different underlying structure.

The buffer superlattice was composed of 30 periods of undoped GaAs/$Al_{0.25}Ga_{0.75}As$ layers. Hall measurements revealed electron density to be $1.35 \cdot 10^{12}$ cm^{-2} for both buffered and non-buffered structures at room temperature. At liquid nitrogen temperature the electron density increased ($2.75 \cdot 10^{12}$ cm^{-2}) in the case of non-buffered structure, and decreased ($1.6 \cdot 10^{11}$ cm^{-2}) for the structure with the supperlattice. Electron mobility increased slightly with cooling from room down to liquid nitrogen temperature for the non-buffered structure, $\mu(300\text{ K}) = 2200$ cm^{2}V^{-1}s^{-1} and $\mu(77\text{ K}) = 2600$ cm^{2}V^{-1}s^{-1}, while substantial increase of the electron mobility ($\mu(300\text{ K}) = 2400$ cm^{2}V^{-1}s^{-1} and $\mu(77\text{ K}) = 66\,000$ cm^{2}V^{-1}s^{-1}) was observed in the buffered case. The width of the narrowest part, or the neck, of the constricted structure was taken $d = (1 \div 3)$ µm.

DC current-voltage (I-V) characteristics revealed quantitative correspondence between the measured electrical resistance of the buffered samples and that evaluated from their geometrical configuration. In the case of non-buffered structure the experimentally measured value of the resistance exceeded the calculated one.

Figure 6 displays photoluminescence spectra of modulation-doped GaAs/AlGaAs structures at 77 K (solid circles) and 300 K (open circles) temperatures for both kinds of the samples. Two groups of peaks can be easily distinguished in the spectra. The first group of the PL lines is located between 1.7 eV−1.9 eV. For the buffered samples, the PL peak in Fig 6b we attribute to the recombination of electron-hole pairs in the $Al_{0.25}Ga_{0.75}As$ layer. Weak intensity shows that the most part of the photogenerated carriers leaves this layer region and recombines in GaAs thus emitting light quanta of lower energy in GaAs layer where the 2DEG is located. At 77 K, more intensive PL in $Al_{0.25}Ga_{0.75}As$ layer than in GaAs for the non-buffered samples can be explained by dominant nonradiative recombination of electrons and holes in 2DEG region through defects and residual impurities. The PL results correlate with electron mobility data: the mobility in 2DEG structures with SL buffer is higher than without it.

Voltage-power characteristics of the samples with buffered and non-buffered structures are presented in Fig 7. Polarity of the microwave-induced voltage in the case of buffered structure corresponded to that of hot carrier thermo electromotive force arising across a semiconductor n-n^+ junction: positive potential emerged on n^+ part of the constricted structure. The sign of the detected voltage agreed with the asymmetry of the I-V characteristic. At room temperature linear dependence of the detected voltage on power was observed up to 1 W of incident microwave radiation, while at liquid nitrogen temperature deviation from linear dependence occurred at lower values of microwave power (see Fig 7a). The non-monotonic character of the voltage-power characteristic we attribute to hot electron transition to higher energetic valleys and to Gunn domains formation under influence of strong microwave electric field. This phenomenon is more power-sensitive at lower temperature when the electrons with higher mobility are more sensitive to electric field strength. Voltage sensitivity was higher for the samples with narrower neck, i.e. or more constricted n-n^+ junction), however this was accompanied by more non-monotonic behavior of the characteristic due to stronger electric field in the junction.

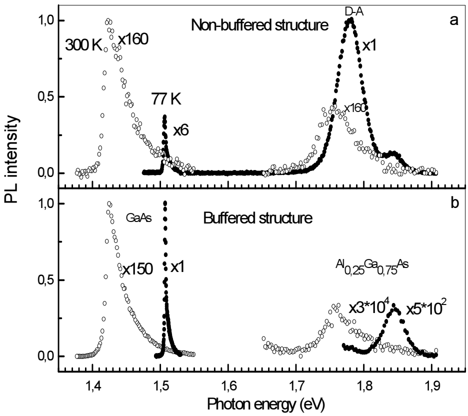
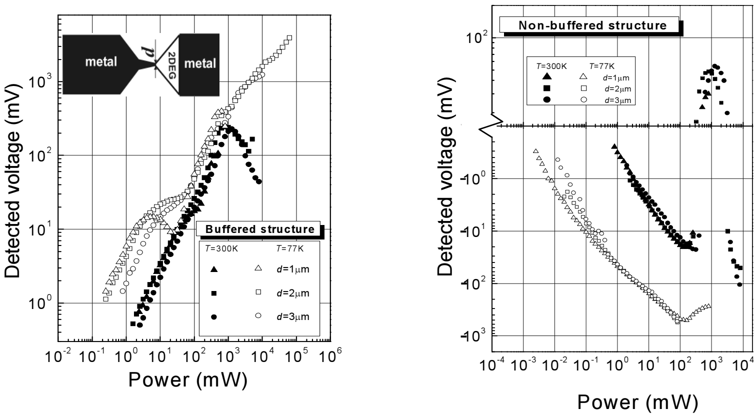


Fig 6. PL spectra of selectively doped $GaAs/Al_{0.25}Ga_{0.75}As$ structure at 77 K (solid circles) and 300 K (open circles) temperatures for two different samples: without (a) and with (b) SL buffer layer

The sensitivity at 77 K was by order higher than at room temperature since electron mobility and energy relaxation time are higher at lower temperatures.

The voltage induced across the ends of non-buffered samples was of opposite polarity (Fig 7b) it corresponded to the asymmetry of the I-V characteristic of the sample.



(a) (b)

Fig 7. Voltage power characteristics of asymmetrically shaped modulation doped structures with (a) and without (b) SL buffer measured at room and liquid nitrogen temperatures. Inset on graph a: schematic top-view of the diode

In this case opposite sign of the detected voltage like the asymmetry of the I-V characteristic, can be explained if supposed the 2DEG channel acted as n^+ region and the part of the sample with the alloyed metal was treated as n region, i.e. had lower carrier concentration.

4. Modulation-doped AlGaAs/GaAs structures with InGaAs layer

However, the drawback of these detectors is their small sensitivity. One solution of this problem is to use semiconductor material with higher carrier mobility, e.g. to use modulation doped structures with two dimensional electron gas (2DEG). To obtain higher mobility of the 2DEG a thin layer of narrow-gap semiconductor may be introduced. Pseudomorphic modulation doped AlGaAs/InGaAs/GaAs heterostructures benefit from higher electron mobility and saturation velocity in the InGaAs quantum well channel accompanied by better confinement properties and higher two dimensional electron gas density when compared to conventional AlGaAs/GaAs heterostructures. From the reason of the difference of a crystal lattice constant InGaAs with small percent of indium is used. The layer should be thin to not step over critical feature thickness, having stepped over feature destroys electrical and optical properties of structure for defects.

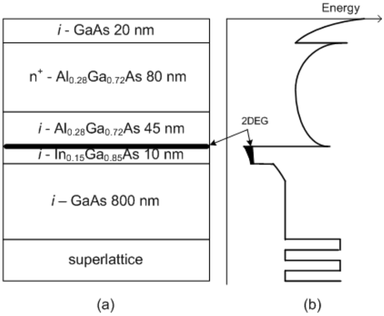


Fig 8. Design of the MBE grown pseudomorphic modulation doped AlGaAs/InGaAs/GaAs structures (a) and energetic band diagram of it (b)

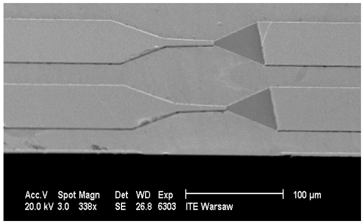


Fig 9. SEM photograph of asymmetrically shaped device

The AlGaAs/InGaAs/GaAs pseudomorphic structures have been grown by molecular beam epitaxy (MBE) technique on semi-insulating GaAs substrate with a superlattice buffer. Figure 8 depicts the schematic view of the structure as well as its energetic band diagram. Electron mobility in the two-dimensional electron gas channel there was $\mu = 6.1 \cdot 10^3$ cm^{2}V^{-1}s^{-1} at room temperature and $\mu = 2.74 \cdot 10^5$ cm^{2}V^{-1}s^{-1} at liquid nitrogen temperature. The lateral dimension of the narrowest part of the asymmetrically shaped structure was in (5÷7) µm range. Fig 9 shows the SEM picture of the asymmetrically shaped AlGaAs/InGaAs/GaAs sample. The sensitivity of the asymmetrically necked structures is proportional to the carrier mobility, as it follows from the phenomenological theory. Thus, if the material with high mobility was used

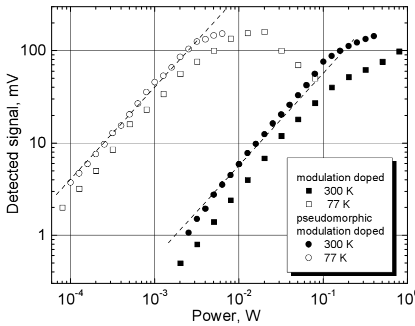


Fig 10. Schematic view of the partly gated microwave diode on the base of asymmetrically shaped modulation doped (MD) semiconductor structure (a) and electron concentration distribution in the diode (b)

the voltage sensitivity of the device should to be higher.

The idea of the increase of electron mobility was implemented by employing the pseudomorphic modulation doped AlGaAs/InGaAs/GaAs structures containing single $In_{0.15}Ga_{0.85}As$ channel. The experiment shows that for 10 GHz the detected signal behaves linearly of low values of microwave power. The decrease in lattice temperature greatly increases the sensitivity of the device: at 300 K it is around 0.6 V/W while, at liquid nitrogen temperature the value reaches 38 V/W, i.e. increases by the factor of more than 60. Comparing this number with the relative increase in the electron mobility with temperature one can infer that the latter effect is mainly responsible for the observed rise in the voltage sensitivity. Power dependence of the detected signal of the pseudomorphic modulation doped AlGaAs/InGaAs/GaAs structure versus and that of the modulation doped AlGaAs/GaAs device, is show in Fig 10. The voltage sensitivity of the AlGaAs/InGaAs/GaAs structure is 2 time higher than that of the modulation doped AlGaAs/GaAs structure.

5. Moduliation-doped AlGaAs/GaAs structures with metal gate

Actually, the microwave detector on the base of the asymmetrically shaped modulation doped semiconductor structure is the asymmetrical version of ungated high electron mobility transistor (HEMT).

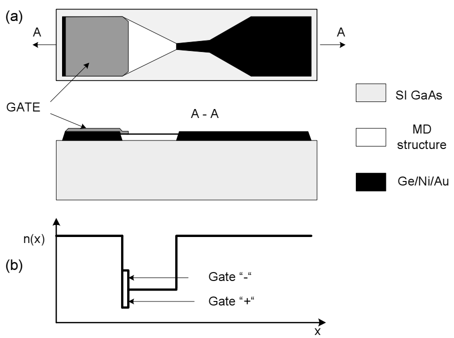


Fig 11. Dependence of the detected signal on microwave power: AlGaAs/GaAs device versus the pseudomorphic AlGaAs/InGaAs/GaAs modulation doped device

The main idea to increase the voltage sensitivity of the microwave diode on the base of asymmetrically shaped modu- lation doped semic- onductor structure lies in the possibility to change electron concen- tration in the 2DEG channel by applying gate voltage to it. As a gate voltage we intend to employ the voltage detected on the asymmetrically shaped microwave diode with one of the metallic contacts of the diode partly introduced over the 2DEG channel as it is shown in Fig 11. Depending on the polarity of the detected voltage different distribution of the electrons in the 2DEG channel can be achieved.

Hall measurements revealed electron concentration $n_s = 1.35 \cdot 10^{12}$ cm^{-2} in the 2DEG channel at room temperature. At liquid nitrogen temperature the measured electron concentration in the channel was by one order lower ($n_s = 1.6 \cdot 10^{11}$ cm^{-2}). Electron mobility in the 2DEG channel at room temperature was $\mu(300) = 2400$ $cm^{-2}V^{-1}s^{-1}$ and increased substantially with cooling: at liquid nitrogen temperature it reached it reached the value of 66 000 $cm^{-2}V^{-1}s^{-1}$. The samples with different width of the „neck“ d = (1÷3) μm were fabricated.

Fig 12 depicts the dependence of the detected voltage on microwave power of the ungated diodes MWD (circle points) and gated diodes MWDG (triangle points) measured at f = 10 GHz frequency. The voltage sensitivity of the MWD at room temperature was 0.2 V/W, while at liquid nitrogen temperature in increased by two orders and reached the value of 20 V/W. Almost by three orders higher values of the voltage sensitivity were measured in the case of the gated microwave diodes: at room temperature S(300) = 200 V/W, and at liquid nitrogen temperature S(77) = 100 kV/W. It is worth noting that even at room temperature the voltage sensitivity of the gated diodes was by one order higher than that of the ungated ones at liquid nitrogen temperature. This finding should facilitate and simplify the application of those gated microwave diodes. Extremely high voltage sensitivity of the MWDG at liquid nitrogen temperature makes it possible to detect microwave signals in nano watt power range.

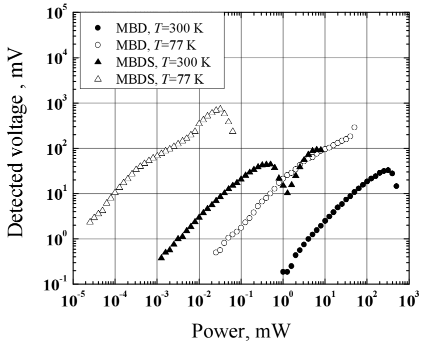


Fig 12. Voltage power characteristic of the ungated (circle points) and gated (triangle points) microwave diodes measured at room and liquid nitrogen temperatures

Sight worthy dependence of the voltage sensitivity of the MWDG on the width of the 2DEG channel in the narrowest part of the asymmetrically shaped structure was observed, Fig 13 depicts the voltage power characteristic of the gated diodes with different width of the „neck“. At room temperature the voltage sensitivity is in inverse ratio with the width of the „neck“: 490 V/W at 1 μm „neck“; 320 V/W at 2 μm „neck“; and 190 V/W at 3 μm „neck“. However, the microwave diodes on the base of asymmetrically shaped modulation doped structure with the gate above the part of the 2DEG channel attract attention from engineering point of view due to their high voltage sensitivity at room temperature and extremely high sensitivities at cryogenic temperatures.

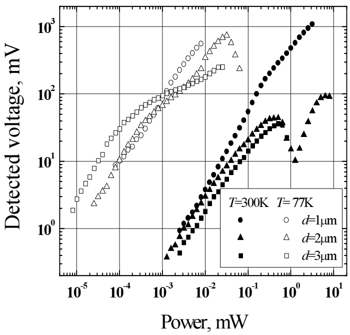


Fig 13. Voltage power characteristic of the gated microwave diodes with different width *d* of their neck measured at room and liquid nitrogen temperatures

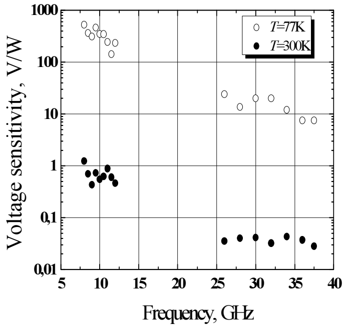


Fig 14. Frequency dependencies of the voltage sensitivity of the gated microwave diodes after the impact of microwave radiation measured at room and liquid nitrogen

Frequency dependencies of the voltage sensitivity of the gated microwave diodes after the impact of microwave radiation measured at room and liquid nitrogen temperatures are presented in Fig 14. The width of the „neck“ of the diode was 3 μm. More pronounced frequency dependence of the voltage sensitivity was observed at liquid nitrogen temperature: the sensitivity decreased from 530 V/W at 8 GHz down to 7.5 V/W at 37.5 GHz.

General Conclusions

1. The sensitivity of symmetrically and asymmetrically narrowed microwaves diodes depends on the thickness of the neck of the diode structure and tend to increase when applying semiconductor materials with high carrier mobility.
2. The polarity of the detected voltage on the microwave diodes produced from asymmetrically narrowed AlGaAs/GaAs structures with superlattice buffer layer and with the wider separating layer corresponds to the polarity

of thermal electromotive force of hot electrons and to the sign of asymmetry of the sample I-V characteristic. The effective heating of the carriers was present within 2DE channel. The presence of the superlattice buffer layer determines the quality of the 2DE channel.

3. When metallized field of asymmetrically narrowed microwave diode has lower electrical conductivity compared to 2DE region, then the polarity of the defected voltage and the sign of I-V characteristic asymmetry are opposite to the sign of the diode with superlattice.
4. There has been exhibited obvious influence of the quality of the 2DE channel on the polarity of the detected signal and its magnitude depending on the thickness of the separating layer.
5. Inserting of additional InGaAs layer into the narrowed asymmetrical selectively doped AlGaAs/GaAs structure, without violating the critical thickness of InGaAs layer, increases the sensitivity of the sensor about 50 %.
6. The microwave diodes produced from asymmetrically narrowed AlGaAs/GaAs structure with metallized gate above the part of the active layer exhibit high voltage sensitivities at room (about 200 V/W) as well as at liquid nitrogen temperatures, due to the fact that electrical parameters are sensitive to the effect of microwave radiation.

List of Published Works on the Topic of the Dissertation

In the reviewed scientific periodical publications

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Publishing, Bristol, 2003), Institute of Physics Conference Series Number 171, Section 8: Novel devices, paper d-240, 2003. ISBN 0750309245 (Thomson ISI Proceedings).

About the author

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ĮVAIRIALYČIŲ $A^{III}B^{V}$ DARINIŲ TYRIMAS MIKROBANGOSE

Bendras disertacinio darbo apibūdinimas

Tiriamoji problema ir darbo aktualumas. Šiuolaikinės puslaidininkių elektronikos vystymąsi didele dalimi nulemia fundamentalieji tyrimai puslaidininkių fizikos srityje. Svarbią vietą užima puslaidininkių, esančių stipriuose elektriniuose laukuose, savybių tyrimas elektromagnetinės mikrobangų spinduliuotės ruože. Šiuo metu pagrindinė elektronikos vystymosi kryptis – nanoelektronika, kuri netolimoje ateityje pakeis tradicinę mikroelektroniką. Mažinant puslaidininkinių elementų matmenis ir tiriant fizikinius procesus, vykstančius juose veikiant elektromagnetine spinduliuote, atsiranda nauji reiškiniai, kuriuos ištyrus, galima kurti naujus prietaisus arba tobulinti jau žinomus. Sparčiai besivystant elektroninėms sistemoms, pastaruoju metu ypatingai išaugo susidomėjimas elektromagnetinės spinduliuotės detekcijos sistemomis.

Iki šiol sukurti puslaidininkiniai (Si, Ge) elektromagnetinės spinduliuotės jutikliai nepasižymi dideliu jautriu. Panaudojus įvairialyčius darinius galima pagerinti bandinių jautrį, nes krūvininkų pakaitinimas puslaidininkyje yra tiesiog proporcingas jautriui. Įvairialytėje sandūroje susidaręs dvimačių elektronų (2DE) kanalas leidžia pasiekti itin dideles krūvininkų judrio vertes, todėl galima padidinti tokių jutiklių jautrį. Mažinant jutiklių matmenis, taip pat galima padidinti jutiklių jautrį, tačiau didėja ir jutiklių varža. Todėl vienas iš sprendimo būdų – naudoti puslaidininkines medžiagas su dideliu krūvininkų judriu. Tokie jautrūs karštųjų krūvininkų diodai paprastai naudojami mažos galios elektromagnetinės spinduliuotės signalų detekcijai. Svarbu, kad šie jutikliai detektuotų elektromagnetinę spinduliuotę tiesiogiai, be išorinės įtampos postūmio. Tai ženkliai supaprastina mikrobangų elektromagnetinės spinduliuotės imtuvų konstrukciją, didina jų patikimumą, mažina kainą ir jie tampa universalesni taikymuose.

Darbo tikslai. Padidinti susiaurintų spinduliuotės jutiklių jautrį bei nustatyti bandinių struktūros įtaką detektuojamam signalui.

Darbo uždaviniai

1. Ištirti mikrobangų spinduliuotės poveikį susiaurintiems puslaidininkiniams dariniams ir atskleisti stebimų efektų fizinę prigimtį.
2. Ištirti susiaurintų įvairialyčių puslaidininkinių darinių savybes priklausomai nuo darinių sluoksnių kokybės ir nuo puslaidininkinių medžiagų parametrų.
3. Ištirti mikrobangų jutiklių savybes, priklausančias nuo selektyviai legiruoto darinio, stipriai legiruoto puslaidininkinio sluoksnio laidumo nuo skiriamojo sluoksnio storio ir nuo sklendės pobūdžio metalizacijos.
4. Įvertinti AlGaAs/GaAs, AlGaAs/InGaAs/GaAs ir GaAs darinių praktinio panaudojimo galimybę kuriant mikrobangų spinduliuotės jutiklius.

Mokslinis naujumas

1. Pirmą kartą tirta įvairialyčių susiaurintų selektyviai legiruotų AlGaAs/GaAs darinių su skirtingais skiriamųjų sluoksnių storiais, su supergardelės buferiniu sluoksniu, naudojant sklendės pobūdžio metalizaciją, ir pseudomorfinių AlGaAs/InGaAs/GaAs darinių savybės mikrobangiuose laukuose.
2. Parodyta, kad veikiant susiaurintus įvairialyčius darinius mikrobangų spinduliuote, atsiranda elektrovara, kurios charakteris ir kiekybiniai parametrai priklauso nuo darinių sluoksnių kokybės, nuo puslaidininkinių medžiagų parametrų bei mikrobangų dažnio.
3. Pasiūlyta submikrometrinių matmenų mikrobangų jutiklio konstrukcija su nesimetriškai ir simetriškai susiaurintais dariniais mikrobangų detekcijai aptikti.

Disertacijos praktinė vertė. Gauti rezultatai gali būti panaudoti kuriant mikrobangų spinduliuotės jutiklius, kurie detektuoja elektromagnetinę spinduliuotę tiesiogiai, be išorines įtampos postūmio.

Ginamieji teiginiai

1. Eksperimentiškai nustatyta, kad nesimetriškai ir simetriškai susiaurintų mikrobangų diodų voltvatinis jautris priklauso nuo diodų struktūros kaklelio pločio ir didėja panaudojant puslaidininkines medžiagas su dideliu krūvininkų judriu.
2. Papildomo nelegiruoto InGaAs sluoksnio įterpimas susiaurintuose selektyviai legiruotuose AlGaAs/GaAs mikrobangų dioduose tarp skiriamojo i-AlGaAs sluoksnio ir nelegiruotojo i-GaAs sluoksnio, neperžengus InGaAs kritinio sluoksnio storio, padidina jutiklių voltvatinį jautrį tiek skystojo azoto, tiek kambario temperatūrose.
3. Naudojant nesimetriškai susiaurintuose selektyviai legiruotuose AlGaAs/GaAs mikrobangų dioduose sklendės pobūdžio metalizaciją virš aktyviojo sluoksnio, galima žymiai padidinti diodų voltvatinį jautrį tiek kambario, tiek skystojo azoto temperatūrose.

Rezultatų aprobavimas. Disertacijos tema paskelbtos 10 mokslinių publikacijų, iš jų 6 straipsniai žurnaluose su Thomson ISI Web of Science citavimo indeksu, 1 straipsnis žurnale Thomson ISI Master Journal List duomenų bazėje, 3 straipsniai tarptautinių konferencijų recenzuotų pranešimų leidiniuose, recenzuotame MII duomenų bazėse Thomson ISI Proccedings. Disertacijos rezultatai aptarti 7 tarptautinėse, 1 užsienio ir 2 nacionalinėse konferencijose. Išspausdintos 3 mokslinės publikacijos konferencijų pranešimų rinkiniuose.

Darbo apimtis ir struktūra. Disertaciją sudaro įvadas, 3 pagrindiniai skyriai, darbo išvados, nuorodos į 86 literatūros šaltinius, pateiktas 10 publikacijų disertacijos tema sąrašas. Iš viso 102 puslapiai teksto, 55 paveikslai.

Pirmajame skyriuje apžvelgiami elektromagnetinės spinduliuotės detektavimo principai, aptariama šiluminės ir bigradientinės elektrovaros susidarymo priežastys, AlGaAs/GaAs įvairialytė sandūra, selektyvusis legiravimas bei puslaidininkių prietaisų fizikinės galimybės. Antrajame skyriuje pateikta eksperimento tyrimo metodika. Išsamiai aprašyti pagrindinės bangos stačiakampiame bangolaidyje sklidimo ypatumai ir perduodama galia. Pateiktos jutiklių voltvatinių charakteristikų matavimų stendų schemos bei voltamperinių charakteristikų blokinė schema. Aprašytas bandinių auginimas molekulių pluoštų epitaksijos būdu ir šiuo būdu užaugintų susiaurintų n-GaAs, AlGaAs/GaAs, AlGaAs/InGaAs/GaAs darinių sluoksnių sandaros, technologiniai gamybos procesai. Trečiajame skyriuje pateikti šių darinių eksperimentinių tyrimų rezultatai, gauti tiriant bandinius elektromagnetine spinduliuote. Disertacijos pabaigoje pateiktos išvados bei cituojamos literatūros sąrašas.

Bendrosios disertacijos išvados

1. Asimetriškai ir simetriškai susiaurintų mikrobangų diodų jautris priklauso nuo diodų struktūros kaklelio pločio ir didėja panaudojant puslaidininkines medžiagas su dideliu krūvininkų judriu.
2. Mikrobangų diodų, pagamintų iš nesimetriškai susiaurinto AlGaAs/GaAs darinio su supergardelės buferiniu sluoksniu ir su platesniu skiriamuoju sluoksniu, detektuotos įtampos poliškumas atitiko karštųjų elektronų šiluminės elektrovaros poliškumą ir bandinio VACH asimetrijos ženklą. Efektyvus krūvininkų kaitimas vyko 2DE kanale. Supergardelės buferinio sluoksnio buvimas lemia 2DE kanalo kokybę.
3. Kai nesimetriškai susiaurinto mikrobangų diodo metalizuota sritis pasižymi mažesniu elektriniu laidumu nei 2DE sritis, tai jos detektuotos įtampos poliškumas ir VACH asimetrijos ženklas yra priešingi diodo su supergardele ženklui.
4. Parodyta akivaizdi 2DE kanalo kokybės įtaka detektuojamo signalo poliškumui ir jo dydžiui nuo skiriamojo sluoksnio storio.
5. Įterpimas papildomo InGaAs sluoksnio į susiaurintą nesimetriškai selektyviai legiruotą AlGaAs/GaAs darinį, neperžengus InGaAs kritinio sluoksnio storio, padidina jutiklio jautrumą apie 50 %.
6. Mikrobangų diodai, pagaminti iš nesimetriškai susiaurinto AlGaAs/GaAs darinio su metalizuota sklende virš aktyviojo sluoksnio dalies, pasižymi dideliais voltvatiniais jautriais kambario (apie 200 V/W) ir skystojo azoto temperatūrose – elektriniai parametrai yra jautrūs mikrobangės spinduliuotės poveikiui.

Trumpos žinios apie autorių

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Antoni Kozič

INVESTIGATION OF $A^{III}B^{V}$ HETEROSTRUCTURES UNDER THE ACTION MICROWAVE RADIATION

Summary of Doctoral Dissertation
Physical Sciences, Physics (02P), Condensed Materials: electronic structure; electric, magnetic and optical properties; superconductors; magnetic resonance; relaxation; spectroscopy (P 260)

Antoni Kozič

ĮVAIRIALYČIŲ $A^{III}B^{V}$ DARINIŲ TYRIMAS MIKROBANGOSE

Daktaro disertacijos santrauka
Fiziniai mokslai, fizika (02P), kondensuotos medžiagos: elektroninė struktūra, elektrinės, magnetinės ir optinės savybės, superlaidininkai, magnetinis rezonansas, relaksacija, spektroskopija (P 260)

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