Preparation and Optimization of Low-Temperature-Grown GaAs Photomixers

Von der Fakultät für Elektrotechnik und Informatik
der Rheinisch-Westfälischen Technischen Hochschule Aachen
zur Erlangung des akademischen Grades
eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von
Diplom-Ingenieur

Martin Mikulics
aus Chomutov, Tschechische Republik

Berichter Universitätsprofessor Dr. H. Lüth
Universitätsprofessor Dr. Ing. R. Waser

Tag der mündlichen Prüfung 6. Juli 2004

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To my parents.
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Chapter 1

Introduction

In the last decade scientific research has reached big progress in production of semiconductor sources of coherent millimeter wave radiation. Since the development of laser, optical heterodyne conversion (photomixing) has been very useful for coherent detection in many regions of the electromagnetic spectrum. Approximately three decades ago, photomixing was nominated as a technique for generating coherent radiation in the microwave and millimeter wave regions [1]. An interest in this technique has been revived recently by the advances in the high-speed III-V device technology. Brown [2] and co-workers made the work at MIT Lincoln Lab [3] that allows direct use of the recently discovered sub-picosecond carrier lifetime in low temperature grown (LT) GaAs. The figure 1.1 shows that despite the fact that photomixing process in LT GaAs has low efficiency in comparison with another sources at the frequencies up to 1 THz, for higher frequency range is the application necessarily. With dynamic progress in optical

![Graph showing power versus frequency for different sources of coherent millimeter wave radiation]

**Figure 1.1:** Review of sources of coherent millimeter wave radiation.

- **Gunn oscillators**
  + reliable and compact technique
  - low power $f > 1$ THz, expensive

- **Backward-wave oscillators**
  + good tunable
  - expensive

- **FIR lasers**
  + high power at $\sim 1$ THz
  - only discrete frequencies possible
  - consume large amounts of power

- **Laser mixing in LT GaAs**
  + up to 5 THz, tunable
  - low efficiency
fiber communication systems the photodetectors built on the low-temperature-grown GaAs have become promising. Their utilizing could lead to an increase of the transfer speed of data in both local application as well as global communication systems.

The aim of my work is to propose and construct the photomixer structures regarding maximal output power. Motivation for increasing THz power is to allow the use a photomixer as a local oscillator in a compact heterodyne receiver for space borne atmospheric and astrophysical studies. According to the latest data, maximum output power is still one order of magnitude lower for this application. Output power of photomixer devices is limited by maximum input power, which could not be higher as thermal damage threshold of the device. At the higher input power, the photomixer burn out through a combination of incident power and ohmic heating from the produced photocurrent. The possibility how to reduce overheating effects will be presented in this work. Native GaAs as a mother substrate has relatively low thermal conductivity (0.46 W/cm.K). Due to this low thermal conductivity there exist two possibilities how to solve the problem. Firstly, it is possible to grow LT GaAs on Silicon, however there exists a well know difficulty concerning lattice constant mismatch, not stable physical properties of so prepared material. In our work we are interested in Lif-off technique. This technique allows to replace LT GaAs layer from GaAs substrate with any substrate having higher thermal conductivity. Firstly, properties of replaced LT GaAs layer on fabricated simply photoswitches and MSM photodetectors have been studied. Several possibilities to increase output power from photomixers will be present. In Chapter 2 will an optimization of properties LT GaAs material by change of growth temperature and its doping be introduced. The mentioned part will also present modification of GaAs material by implantation process. Technology, which was used for fabrication of photodetector, photoswitches and photomixer devices will be presented in Chapter 3. The principle of measurements methods needed for characterization of fabricated devices will be introduced in Chapter 4. In Chapter 5 optimization of metallic contacts fabricated on LT GaAs and improvement in the process of collection of created photogenerated carriers due to the optimization of device MSM geometry will be discussed. An optimization and characterization of photomixer devices will be presented in Chapter 6.

1.1 Terahertz technology and applications

It is well known that an organic and inorganic molecules could be studied by their vibrational and rotational transitions, which lie in the 0.1–10 THz range. This range of electromagnetic waves is also called the "THz Gap" as shows in figure 1.2. As one can see in figure 1.2, research on THz radiation does not include electromagnetic fields of present wireless telecommunication systems, being its frequency about three order of magnitude higher than mobile phone frequencies and two orders higher than the most advanced satellite systems. Unfortunately, nowadays progress in production of usable sources of THz radiation does not allow their massive use for spectroscopic application. This is due to several difficulties connected with the principle of these devices. CO2 lasers, used as a sources of THz radiation, are in general robust, complicated and
consume large amounts of power. The reason for high interest in optical heterodyne conversion in photomixers lies in its simplicity and in the fact that this source is relatively good tunable in large range of output frequency.

1.1.1 Molecular spectroscopy

Spectroscopy in the terahertz (THz) region of the electromagnetic spectrum is an important and growing field of research with a broad range of applications. The characteristic properties of THz radiation, localized between the infrared and the microwave frequencies, suggest many applications in the spectroscopy of gases, liquids and condensed matters. GREAT (German Receiver for Astronomy at Terahertz Frequencies) a heterodyne instrument for high-resolution spectroscopy aboard SOFIA (Stratospheric Observatory for Infrared Astronomy) is in development by a consortium of German research institutes.

SOFIA is an airborne observatory that will study the universe in the infrared spectrum. Besides this contribution to science progress, SOFIA will be a major factor in the development of observational techniques, of new instrumentations and in the education of young scientists and teachers in the discipline of infrared astronomy.

![THz Gap Diagram]

Figure 1.2: The graphical representation of THz gap.

1.1.2 Genetic diagnostics with integrated THz systems

Novel spectroscopic tools in the THz range will be used to provide a basic understanding of genomic information, by deciphering gene expression and determining protein function and protein interactions. This will also contribute to structural genomics by determining, more effectively and at a higher rate than is currently possible, the 3-D structure of macromolecules e.g. proteins. It will provide an information concerning the function of proteins and enzymes in relation to their structure. This requires spectroscopic techniques that probe structural properties and allow high temporal resolution. Among the variety of spectroscopic techniques, Infrared (IR) spectroscopy has probably the best access to minute structural details, in the order of fractions of a bond dimension. In the mid-IR spectral range, in particular in the region from 2000-1000 cm$^{-1}$, FT-IR spectroscopy can monitor alterations at individual bonds even in large protein complexes, thus allowing structural and conformational changes in the course of a biological reaction to be monitored in high detail and in real time, and reaction mechanisms to be elucidated.
It was previously presented by the Haring [4] that label-free sensing approach for the label-free characterization of genetic material with terahertz (THz) electromagnetic waves. The figure 1.3 [4] shows the simple scheme of measurements set-up for Time-resolved THz analysis. This research of polynucleotides demonstrates a strong dependence of the complex refractive index of DNA molecules in the THz frequency range on their hybridization state. By monitoring THz signals (see figure 1.4) it is possible to infer the binding state (hybridized or denatured) [5] of oligo- and polynucleotides, enabling the label-free determination the genetic composition of unknown DNA sequences. A broadband experimental proof-of-principle in a freespaces analytic configuration, as well as a higher-sensitivity approach using integrated THz sensors reaching femtomol detection levels and demonstrating the capability to detect single-base mutations, show big potential application for further generations.

Figure 1.3: The simple scheme of measurements set-up for Time-resolved THz analysis (according [4]).

Figure 1.4: Magnitude of the transmission parameter $S_{21}$ of the bandpass filters loaded with denatured or hybridized DNA films on top (5.4 kb vector pcDNA3). In comparison, the measured and simulated reference data of the unloaded filter (according [5]).

1.2 Photomixing

Following part presents the principle of photomixing. Photodetector is the major part of photomixer device therefore beginning of this chapter the theory of MSM photodetectors will be introduced.

1.2.1 Metal-semiconductor-metal photodetectors

Photodetector is a semiconductor-based appliance that can detect optical signals. Such a device is important for the optical-fiber communication systems and other various
applications based on registration of photons. The photodetector in communication system demodulates optical signals, i.e., it converts the variations of optical signal intensity into a variation of the electrical signal, that is subsequently further processed. In order to reliably demodulate optical signal, photodetector must generally satisfy strict requirements such as the high sensitivity at operating light wavelength, the fast enough response to follow signal changes and the minimum device noise.

Photodetectors can be divided into several groups according to the wavelength to which they are able to respond. Other criterion for classifying photodetectors is a physical phenomenon on which the detector relays in the conversion of photons flux to the electrical signal. The photodetector on which will be focused further utilizes an internal photo effect, i.e., the photons with energy $E_{ph}$ higher than the band-gap energy of semiconductor $E_{g}$ are absorbed in the bulk of the semiconductor material producing electron-hole pairs which are separated by an electrical field. The most common type of such photodetector structures consists of two metallic contacts formed on the light absorbing active layer. Depending on the type of metallic contacts, detectors are divided on photoconductive detectors with ohmic contacts and the barrier detectors having the Schottky contact instead of ohmic one onto the active layer. An arrangement of contacts themselves could be either vertical or planar, with later giving a lower device capacitance, the important parameter limiting the device speed.

1.2.2 Theory of MSM structure

Standard metal-semiconductor-metal photoconductor (MSM) structure consists of a planar electrode system in the shape of interdigitated fingers (figure 1.5). The MSM structure is described by the finger width $l_{w}$, finger distance $l_{f}$, length of fingers $l_{f}$, and a number of finger pairs. The basic parameters of such photoconductor structure are the dark current, breakdown voltage, capacitance of structure, DC responsivity in term of Amper per Watt, and response time that itself depends on the capacity of structure, transit time of the photogenerated charge carriers towards the electrodes, and their lifetime. All these parameters are discussed in details below.

![Figure 1.5: Metal-semiconductor-metal interdigitated finger structure.](image)

1.2.3 Capacitance and time response of the MSM structure

One of the key parameters of the MSM structure is a temporal response to modulated light. The response of interdigitated MSM detector is generally limited by the carrier
transit time of generated carriers, their lifetime, and the RC constant. It is useful show how one can calculate the maximum frequency, in term of -3dB limit, which is limited by temporal response of the device. This frequency is given by the equation [6]:

$$f_{-3dB} = \frac{1}{2\pi \sqrt{(RC)^2 + \tau^2}},$$  

(1.1)

where $R$ is the resistance of device contacts and load (usually it is characteristic impedance of the connected transmission line), $C$ is the capacity of structure and $\tau$ is either the charge carrier lifetime or their transit time. The charge carrier lifetime relates to the basic material properties and it is difficult to change it. The transit time is given by a distance between collecting electrodes, electric field strength and the charge carriers mobility. The capacity of device, depends on layout of the MSM structure. Let us consider structure shown in figure 1.5. The capacitance of such device is described by following equation [7]

$$C = \frac{\varepsilon_0 (1 + \varepsilon_r) A}{l_0 + l_w} \frac{K(k)}{K(k')}$$  

(1.2)

where $\varepsilon_0$ and $\varepsilon_r$ are permittivity of vacuum and relative permittivity of semiconductor material, respectively, $A$ is an active area of the MSM structure, $l_0$ is a distance between fingers and $l_w$ is the width of fingers. The function $K(k)$ and $K(k')$ are complete elliptic integrals:

$$K(k) = \int_0^{\pi/2} \left[ \frac{1}{\sqrt{1 - k^2 \sin^2 \phi}} \right] d\phi$$  

(1.3)

$k$ and $k'$ is expressed as

$$k = \tan^2 \frac{\pi l_w}{4(l_0 + l_w)} \quad \text{and} \quad k' = \sqrt{k^2 - 1}.$$  

(1.4)

It is seen from equation (1.2) that capacitance of the MSM structure increases when a distance between fingers decreases. Moreover, there are many possibilities how to design the MSM structure for optimal capacitance of the devices, especially, when the DC response of device is considered too. Usually, one requires the MSM device with capacitance as small as possible on one side and the maximized DC-responsivity on the other. DC responsivity will be described in details later. These two conditions are in controversial and final design of the MSM device is always a trade-off. Figure 1.6 displays a capacitance of the MSM structure with total active are of 2500 $\mu$m$^2$ for various finger widths and distances between fingers. Furthermore, it is very interesting to show the tendencies representing by formula (1.2). For instance, for all cases one can see that for some finger spacing with increases of finger thickness the value of capacity has a tendency to increase and goes through maximum. From graphic representation one can say that the all functions calculated from formula (1.2) have only one extreme for parameter $l_0$=constant. This point is global maximum and from this reason is called supremum with its position at about $l_w = l_0/2$. The situation described before is well seen for the finger distance $l_w=1\mu$m, where the maximum is around 0.5 $\mu$m for finger
width. While figure 1.6 speaks about general tendencies in the capacitance of MSM structure, figure 1.7 serves as a quick reference to capacitance of MSM interdigitated structure for several $l_d/l_w$ ratios. In this graph values of capacitance for a virtual structure with an active area of $1\mu m^2$ are plotted.

Figure 1.6: Theoretical values of capacitance of interdigitated MSM structure for various finger width $l_w$ and finger spacing $l_d$.

### 1.2.4 DC-Responsivity of MSM structure

The responsivity of photodetector is described by a ratio of the photoelectric current $I_{ph}$ which is induced by an incident light in the device, and optical power $P_{opt}$ impinging

Figure 1.7: Theoretical values of capacitance of MSM structure for finger spacing/finger width $l_d/l_w = 1, 2, 4$. 
on detector:

\[ R = \frac{I_{ph}}{P_{opt}}. \tag{1.5} \]

If each photon with an energy \( E = h\nu \) generates an electron-hole pair that is completely collected at the electrodes, then the maximum responsivity is limited by a photon wavelength \([8]\):

\[ R = \frac{\lambda}{1.24}, \tag{1.6} \]

where \( \lambda \) is the wavelength in \( \mu \text{m} \) unit. A light impinging onto semiconductor surface has to pass through an interface between two optically different mediums. Therefore light subjected to the reflection of the electromagnetic waves. A fraction \( r \) of the incident light beam reflected from the semiconductor surface is

\[ r = \left( \frac{n_a - n_s}{n_s + n_a} \right)^2, \tag{1.7} \]

where \( n_s \) and \( n_a \) are the refractive indexes of the semiconductor and air, respectively. In this aspect, inserting an special layer with refractive index \( n_{AR} \) of value between \( n_s \) and \( n_a \) should reduce reflection. The optimal value for \( n_{AR} \) is a geometrical mean of \( n_s \) and \( n_a \). The thickness of such antireflective coating (AR) layer chosen is to obtain near zero reflection at a certain wavelength \( \lambda_0 \). The optimised optical distance \( n_{AR} d_{AR} \) of the AR coating layer must be equal to a quarter of the wavelength so:

\[ d_{AR} = \frac{\lambda_0}{4 n_{AR}}, \tag{1.8} \]

where \( d_{AR} \) is thickness of the AR coating layer. For instance the SiNx with \( n_{AR} = 1.85 \) can be used as antireflection coating and as a passivation layer of the device.

The amount of light passing through the device absorption layer decreases exponentially with travelled distance. Due to absorption for a device with a thickness \( d \) of the absorption layer the fraction of light flux \( \Phi_0/\Phi_0 \) that is absorbed is than

\[ \phi = \phi_0 (1 - e^{-\alpha d}), \tag{1.9} \]

where \( \Phi_0 \) is photon flux incident on device surface, \( \alpha \) is the absorption coefficient at given wavelength. This absorption law is important for a calculation of absorption efficiency \( \eta \) of the light in the device

\[ \eta = (1 - r)(1 - e^{-\alpha d}). \tag{1.10} \]

It can be supposed that the photon flux density \( \phi(\lambda) \) is incident on the detector of area \( A \). The basic expression describing the short circuit photocurrent \( I_{ph} \) at zero frequency (DC), i.e., an increase in the device current above the dark current accompanying illumination is

\[ I_{ph} = q \eta \phi_0 A g, \tag{1.11} \]
1.2. PHOTOMIXING

where \( q \) is elemental charge, \( g \) is a photoconductive gain determined by the properties of the photodetector—namely by its contact layout, composition and optical length of absorbing layer, and drift conditions for photogenerated charge carriers.

To calculate the photocurrent we adopt several simplifications. We supposed that the levels of illumination and the electric field are weak, so that the charge carrier drift velocity is proportional to the electric field strength and the recombination of excess charge carriers is linear. Further, let the excess carrier lifetime be the same for majority and for minority charge carriers and we take an one-dimensional approach. This is to justify a detector thickness, \( d \), that is small with respect to the charge carrier diffusion length. Finally, the effect of recombination at front and rear surfaces is also neglected. The basic expression describing photoconductivity in semiconductors under above mentioned conditions and under steady-state excitation is then

\[
I_{ph} = \Delta \sigma V_b = q \frac{w d (\Delta n \mu_n + \Delta p \mu_p)}{L_d} V_b,
\]

where \( \mu_n \) and \( \mu_p \) are the electron and hole mobilities, respectively, \( V_b \) is the bias voltage, \( \Delta n \) and \( \Delta p \) are photogenerated charge carrier concentrations, \( w \) is the width of photoconductor, and \( L_d \) is the distance between electrodes. Taking into account a steady-state illumination and assuming uniform and complete absorption of the light in the detector, the rate equation for the excess carriers concentration in the sample are

\[
\frac{d\Delta p}{dt} = \phi \eta - \frac{\Delta p}{\tau_p} = 0 \quad \text{and} \quad \frac{d\Delta n}{dt} = \phi \eta - \frac{\Delta n}{\tau_n} = 0
\]

where \( \tau_n \) and \( \tau_p \) are the excess carrier lifetimes for electron and holes, respectively. These lifetimes can be expressed as

\[
\tau_n = \frac{\Delta n}{\eta \rho_n} \quad \text{and} \quad \tau_p = \frac{\Delta p}{\eta \rho_p}
\]

for electron and hole excess concentrations, respectively. Photoconductive gain \( g \) in a sense of expression (1.11) then yields

\[
g = d(\tau_n \mu_n + \tau_p \mu_p) \frac{V_b}{\bar{I}^2} = d \left( \frac{\tau_n}{\bar{I}^2 / \mu_n V_b} + \frac{\tau_p}{\bar{I}^2 / \mu_p V_b} \right)
\]

or in the terms of charge carriers transit times

\[
g = \left( \frac{\tau_n}{\bar{t}_n} + \frac{\tau_p}{\bar{t}_p} \right) d,
\]

where \( \bar{t}_n \) and \( \bar{t}_p \) are the transit times of electrons and holes between contacts, respectively. This means that the photoconductive gain is given by the ratio of photogenerated charge carrier lifetime to the transit time for both types of charge carriers. The photoconductive gain can be less than or greater than unity depending upon whether the drift length, \( L_d = \bar{u} \tau \), is less than interelectrode spacing \( L_d \). We recall the expression for the DC responsivity from the very beginning of this chapter and we include
all discussed losses of impinging light. Final formula for the MSM interdigitated photodetector illuminated with monochromatic photons is

\[ R_{DC} = \frac{L_a}{L_a + L_b} \frac{\lambda}{1.24} \frac{(\tau_e \mu_e + \tau_h \mu_h) V_b}{\tau_a^2} \left(1 - r\right)\left(1 - e^{-ad}\right), \]  

where fraction \( L_a/(L_a + L_b) \) stands for area of the MSM uncovered with contacts metal. This expression shows clearly the basic requirements for high photoconductive responsivity at a given wavelength \( \lambda \): i/ absorption efficiency \( \eta \) close to unity; ii/ long excess carrier lifetimes, iii/ the smallest possible interelectrode distance \( L_a \); iv/ the highest possible mobility of carriers; v/ the highest possible operation voltage \( V_b \). The frequency dependent responsivity \( R_{\omega} \) can be determined by relation

\[ R_{\omega} = R_{DC} \frac{1}{(1 + \omega^2 \tau_{eff}^2)^{1/2}}, \]

where \( \tau_{eff} \) is the effective response time of the photodetector structure. The contribution \( L_a/(L_a + L_b) \) is a geometrical factor, which describe ratio between an area which is actually illuminated to the total MSM area. It is clear that using a narrower fingers one gets larger illuminated area of the MSM structure. However, the traveling distance for charge carriers increases too and DC response has tendency to decrease (distance between fingers is in denominator in square).

![Graph](image)

Figure 1.8: Theoretical values of capacitance and DC responsivity of MSM structure.

Therefore, final geometrical factor which relatively well describes the real situation has a form \( 1/L_a \cdot (L_a + L_b) \). This can be seen in the figure 1.8, where theoretical values of capacity and DC responsivity of the MSM structure are plotted for various distance between fingers at finger width as a parameter. This graph can be used to consider optimal design of the MSM interdigitated structure. It shows relation between theoretical DC responsivity and the MSM device capacitance. With a help of this graph, one can easily find a compromise between a very low capacitance of structure on the one side, and very high DC responsivity on another.
1.2. PHOTOMIXING

1.2.5 Photomixer design

The output power of a photomixer is described by the following equation [2]:

$$P_{out} = \frac{n_e(V_G G_0)^2 R_a}{2[1 + (\omega \tau_e)^2][1 + (\omega R_a C)^2]}$$

(1.19)

where $n_e$ is the radiation efficiency, $V_G$ is the bias voltage, $R_a$ is the ac load resistance, $C$ is the capacitance of the interdigitated structure, $\tau_e$ is the photocarrier lifetime. The dc photoconductance $G_0$ can be expressed as [2]:

$$G_0 = n_e \sqrt{\frac{m P_1 P_2}{\hbar f} \frac{q \mu_e \tau_e}{\hbar^2}}$$

(1.20)

where $P_1$ and $P_2$ are the input powers of mixed laser signals, $m$ is the mixing efficiency, $\mu_e$ is the photocarrier mobility, $l_a$ is the contact separation and $n_e$ is the external quantum efficiency which depends on the reflection losses, absorption efficiency and finger contacts factor. Experimental data can be well modeled by using these equations [9]. At the same time, these equations show the possibilities to optimize material and device properties. From the practical point of view, it is useful to replace the product $V_G G_0$, which is actually the dc photocurrent, by the responsivity $R_{ph}$ and the input power $P_{in}$, which are simple measurable quantities:

$$V_G G_0 = I_{ph} = R_{ph} P_{in}$$

(1.21)

The output power can be described as a function of only four parameters: $R_{ph}$, $P_{in}$, $RC$ and $\tau_e$. The first three parameters can be simply evaluated from the experiment on the device, but for the last one special additional measurement using ultra-fast electro-optic sampling set-up is needed. We have shown previously that carrier lifetimes of $\sim 0.2$ ps can be obtained in LT GaAs MSM structures and thus ultrafast PDs ($t_e$, $t_f$ and FWHM of 0.4–0.6 ps) can be realized [10]. However, we found that devices with an area of $20 \times 20 \mu m^2$ are $RC$-limited. Calculated output power of a photomixer at 500 GHz as a function of the detector area (i.e. considering the capacitance of 0.02–0.04 F/μm² [11]) is shown in figure 1.9. The output power is normalized for $\tau_e = 0.2$ ps and $C_n = 0.02 F/\mu m^2$ $\tau_e = 0.2$ ps and $C_n = 0.04 F/\mu m^2$. Similar curves are shown for $\tau_e = 1$ ps, considering possible lifetime increase at higher biases [12]. From this it follows that the mixer area should be less than $100 \mu m^2$ to reach the condition $RC < \tau_e$. 
Figure 1.9: Output power of LT GaAs photomizer as a function of the device area.
Chapter 2

Material preparation and characterization

The most desired properties of material designed for the ultrafast photodetectors as well as tuneable photomixers operated in the large frequency range are high resistivity, high mobility of photogenerated charge carriers and high dielectric breakdown strength. These properties have recently been demonstrated in the low temperature grown GaAs [13], that is well known for its subpicosecond charge carriers lifetime [14, 15]. From this reason combination of these properties together makes it one of the best photoconductive material. Till now, there are demonstrated photodetectors based on this material operating at frequencies up to 550 GHz [16] and photomixers producing THz radiation [16, 17].

This chapter is divided into the two parts. In the first one properties of LT GaAs are briefly summarized and the preparation of our samples described. After that, investigations (dark current, responsivity, carrier lifetime, etc.) related to the material structure (different LT GaAs growth temperature and thickness, with and without AlAs interlayer, undoped and Be-doped layers, etc.) are presented. In the second part relatively new member of the large family of implanted GaAs will be also presented, because of its simplicity of preparation of this type of material and its perspective application as the material for high speed photoconductive devices.

2.1 Properties of LT GaAs

The low temperature grown (LT) GaAs is material grown by molecular beam epitaxy (MBE) at substrate temperature as low as 150-300 °C, in contradiction to conventional growth temperature of about 600 °C. After subsequent annealing at temperatures above 600 °C this material becomes highly resistive with resistivity unusually high for epitaxial layer. Typically, resistivity reaches values of $10^8$–$10^9$ Ωcm at 300 K [13]. There are two accepted models to explain properties of the LT GaAs. First one, an formation of internal Schottky barriers from arsenic clusters has been suggested to be the main reason for high resistivity, as well as for a dielectric breakdown field in excess of 3–10$^8$ V/cm [18, 19]. Second model is based on arsenic antisite related defects which are
present in the LT GaAs. These defects form donor-like deep-level states in the order of magnitude up to $10^{19}$ cm$^{-3}$ and act as trapping centers [20]. This high concentration of states gives a rise to free carriers lifetime of the order of a picosecond and compensate any shallow acceptor [14, 15]. The concentration of deep-level states depends on an amount of arsenic excess, that in turn depends sensitively on the growth and annealing conditions of LT GaAs epitaxial layer.

Low temperature molecular-beam epitaxial GaAs layer is typically grown at 150–300°C. At this growth conditions epitaxial layer is still monocrystalline until the critical thickness. Above the critical thickness a formation of extended defects of pyramidal shape starts. This lead to the breakdown of crystallinity of epitaxial layer. At growth temperature of 200°C, a critical thickness of 0.05 μm was reported [21]. Further factors that influence physical properties of LT GaAs epitaxial layers are the As overpressure in the term of As$_4$/Ga beam equivalent pressure ratio (BEP) and the growth rate [13]. However, changes in properties of LT GaAs relate directly to an excess of arsenic incorporated into epitaxial layer. Regardless how this arsenic is finally incorporated, either as precipitates or simple As$_{Ga}$ antisites, it severe to impact the layer properties. It was shown that LT-GaAs contains a high density of arsenic antisites (up $10^{19}$ cm$^{-3}$) in dependence on the growth temperature. High density of As antisites is responsible for the observed ultrashort recombination times [15], although some groups state that the precipitates also play a role in the recombination dynamics [22]. The As$_{Ga}$ point defect is a double donor, which is generally found in the neutral charge state As$_{Ga}^{0}$ and in the single positive charge state As$_{Ga}^{+}$ and acts as a electron trap. Typical concentrations of As is [As$_{Ga}^{0}$] around $10^{16}$cm$^{-3}$ and [As$_{Ga}^{+}$] around $10^{16}$cm$^{-3}$ at the lowest growth temperatures at which crystalline LT GaAs can be grown (200°C). These concentration decreases with increasing grown temperature and so the recombination rate would be lower in the cases then the material is grown at higher grown temperatures.

The LT-GaAs is typical with absorption $\alpha$ of 15000 cm$^{-1}$ near the bandgap wavelength and is comparable in amplitude to the interband absorption for wavelength above the bandgap. The spectral shape of the absorption curves in different publications exhibits the same form, even if the absolute values are different. It is believed it depends on the growth parameters. In the far infrared region an absorption structure around 0.3eV is observable which is related to absorption on the intrinsic acceptor $V_{Ga}$. The absorption structure appears only for annealed samples and increases with the annealing temperature. The annealing of LT-materials leads to decrease of the absorption coefficients of one to two orders of magnitude for the wavelengths below the bandgap. Finally, an absorption due to arsenic precipitates was stated [23].

### 2.1.1 Growth of LT GaAs samples

LT GaAs layers used in this work were grown by Varian Mod GEN II MBE system on indium-free-mounted 2 inch (100) semi-insulating GaAs substrates with the resistivity of $1.5 \times 10^8 \Omega \cdot \text{cm}$. The growth temperature in the range 200°C–300°C was adjusted by a calibrated thermocouple. An As$_4$/Ga beam-equivalent pressure ratio of 19 and a growth rate of 1 μm·h$^{-1}$ were used to growth thick epitaxial layers in the range 0.5 μm
to 1.5 μm. An AlAs etch-stop interlayer with the thickness of 0.3 μm was grown between the substrate and LT GaAs to enable separation of LT GaAs layer from the substrate. The next reason for growth of AlAs interlayer is the role that this layer could electrical isolated GaAs substrate with the generally well-know slow carriers from the LT GaAs layer with ultrafast carriers dynamics. In figures 2.1 and 2.2 we can see details of resonant cavity structure also call Bragg mirror designed for wavelengths in the range of 750 nm–820 nm. Our Bragg mirror consists of 12 period of GaAs/AlAs with the thickness of 55 nm/67 nm.

![Figure 2.1: SEM picture of the edge of the as-cleaved 16044 growth sample. Before wet etching (1μm LT GaAs).](image)

The effect of this configuration on the reflectivity in the dependence on an incident different wavelengths was simulated and the results are shown in figure 2.4. After processing of the MSM photodetectors on this material system the spectral responsivity was measured. From the presented results is clear that Bragg mirror is selective exactly in the wavelengths range, which will be used for illumination of photodetectors and photomixers.

### 2.1.2 Spectral responsivity and Current-Voltage measurements

Photodetectors with an active area 100×100 μm² and with a finger width/spacing of 1/2 μm were fabricated on LT GaAs with Bragg mirror and nitrogen implanted GaAs. Photodetectors were illuminated with the wavelengths in the range 350–1000 nm. In figures 2.3 and 2.4 one can see that the Bragg mirror is selective in the range 750 nm-
Figure 2.2: SEM photograph of the Bragg reflector. Before wet etching.

820 nm what is approximately in the same range which was predicted by the simulation of the reflectivity for 12 periods of GaAs/AlAs with the thickness of 55/67 nm. In the figure 2.4 are shown characteristics for different thickness of GaAs/AlAs layers. As is shown in figures 2.1 and 2.2 there are differences in the thickness of these layers which are produced during MBE process. But through these problems are theoretical and measured data in very good agreement.

In the next properties of photodetectors fabricated on the material with different growth temperature were compared. All samples indicate approximately the same shape of the spectral responsivity curves (see figure 2.5). The maximum of responsivity is detected for the region near to 850 nm, which correspond to the band gap of GaAs at R.T. ~ 1.42 eV. For higher wavelengths responsivity rapidly decreases. On the other hand, shorter wavelengths penetrate to the GaAs material more shallow. Also with higher energy photons for the same energy decrease number of photons. This induced lower value of total number of photogenerated electron-hole pairs. The photocurrent is proportional to this number. Responsivity measurements at 850 nm show that the photodetectors have different responsivity and this depends on the growth temperature (see figure 2.6). With increasing of growth temperature responsivity increases. This is clear because the photocurrent is proportional to the $\mu \times \tau$ product, where $\mu$-mobility and $\tau$-carrier lifetime depends on the growth temperature.

From Current-Voltage characteristics (see figure 2.7) measured without illumination one can see, that materials can be divided into two groups. Samples fabricated on the materials 225 °C and 250 °C indicates linear dependencies of the current up to 10 V bias,
but these characteristics proceed quadratic and from 20 V sub-linear dependences. This is in contradiction to observed characteristics measured on the samples based on the materials growth at temperatures 275°C and 300°C. This results could be by explain by eliminating of overheating effects. It is well known that LTGaAs layers decrease their temperature conductivity by decreasing of growth temperature. In this case good conditions for accumulation of heat in the material are created and with higher electric field higher concentration of free carriers are produced, what contributes to the total dark current. On the other hand in the materials with higher temperature conductivity
Figure 2.7: Current-Voltage characteristics for photodetectors fabricated on the LT GaAs materials with different growth temperature.

is eliminated producing of new free carriers and the total dark current decreases. One of the most important properties on which we are concerning at the designing of the photodetector devices is as low as possible dark current. On the other hand at the same time we need from the device as high as possible photocurrent. Important for our work was to increase the output power of photomixer devices. One of the possibilities is to improve the electrical properties of photodetector devices.

In the next the influence of the thickness of the active LT GaAs layer on the properties of MSM photodetector was studied. As to see from figures 2.8 and 2.9 a 1 µm and 1.5 µm thick LT GaAs layer are compared which were grown on the 300 nm thin

Figure 2.8: Current-Voltage characteristics of MSM photodetectors fabricated on the LT GaAs materials with different thickness.

Figure 2.9: Responsivity characteristics under illumination λ = 850 nm with input power 170 µW.
2.1. PROPERTIES OF LT GaAs

AlAs layer, both samples were grown at the same temperature 275°C. An AlAs layer we used as electrical isolation layer and also for increasing of heat exhaust from the active layer. There was not observed any differences in the dark current curves. For sample with 1.5 μm thick LT GaAs layer there was observed higher responsivity. This is in very good agreement with theory, because incident signa decrease on the 1/e in the depth 1 μm and the rest of the signal is not used. So we lose about 30% of the signal. The material with the higher thickness of the active layer, produces higher number of the created photogenerated carriers. In this case was observed that $P_{1\mu m}/P_{1.5\mu m} = \text{Resp}_{1\mu m}/\text{Resp}_{1.5\mu m}$. For bias 40 V there was measured responsivity for 1 μm and 1.5 μm thick LT GaAs layer structure 39 mA/W and 52 mA/W.

![Figure 2.10: Current-Voltage characteristics of MSM photodetectors. Both materials was grown at the same temperature 275°C. The thickness of the LT GaAs layer is 1.5 μm.](image1)

![Figure 2.11: Current-Voltage characteristics under illumination $\lambda = 850\,\text{nm}$ with input power 70 μW.](image2)

Our next observation concerned to the comparison of the materials with AlAs layer between substrate and active LT GaAs layer and without this interlayer. Both samples were grown at the same temperature 275°C and with the same thickness 1.5 μm. Our results show another tendencies as we thought. As to see from figures 2.10 and 2.11 there are characteristics in this, which show the difference in current-voltage characteristics. We assumed that AlAs interlayer will acts the barrier between LT GaAs layer and the substrate. But as shows our observation the dark current is for the sample with AlAs higher, then for the sample without this interlayer. This could be explained only due to different distribution of electric field in LT GaAs layer, which is near to the AlAs layer.

Doping of LTGaAs material could be one of the way, which could decrease time response of the photodetectors and increase of their response amplitude. But unfortunately we didn’t observed markable enhancements of the properties of our photoconductive devices. Photodetectors based on the material with Beryllium doping in the concentration $10^{19}\,\text{cm}^{-3}$ were compared with the same structures on the material.
without doping. As to see from current-voltage characteristics in figure 2.12, material with Be-doping exhibits higher dark current in whole range of biases. For example at 40 V bias, dark current on the sample with Be-doping is about 5-times higher, then for the undoped material. This could be explained by Hopping conductivity mechanism and will be discussed later in this part. As was spoken earlier as low as possible dark current is needed for our photoconductive devices. On the other hand responsiveness characteristics in the figure 2.13, show approximately one order of magnitude higher responsivity at lower biases, this difference decreases with increasing bias. At the bias of 40 V more than 100% higher responsivity is observed for MSM structures based on Be-doped LT GaAs material. This property is excellent, but as will be shown later in the part about characterization of material through carrier lifetime, this strongly dependents on applied electric field in Be-doped material.

2.1.3 Temperature dependence of LT GaAs conductance

The conductivity in the LT GaAs is completely controllable by the AsGa related defects [13]. These defects pin the Fermi level at their energetic state in the middle of the bandgap of GaAs. Their concentration is sufficient to form a quasi continuous band with a hopping charge transport within it. The defects are so close to each other that charge carriers can jump (hop) from one defect to the other without being transferred into the conduction band. If jump takes place between two neighbor defects, then temperature dependence of hopping conductivity is given by $\exp(-\Delta E_{\text{hop}}/k_B T)$, where $\Delta E_{\text{hop}}$ is activation energy of the hopping process. The figure 2.14 shows temperature dependence of the conductivity of LT GaAs layers grown at 220°C and 250°C and with and without Be-doping. The measured resistance consists of the sheet resistance.
of the layer of LT GaAs itself and from resistance of contacts. But from the further results which will be presented later in the part 5.1 (see Chapter 5) about optimization of metallic contacts of MSM structure we can make approximation that the values of total resistance which were measured are same as the sheet resistance of LT GaAs layers. This is possible because values of the ohmic contacts are less then 1% of the values of sheet resistances. As shown in figure 2.14 the total conductivity of the circular TLM structures with temperature follows two different activation energies. We fitted measured values by the formula 2.1.

\[ \sigma(T) = A_1 \cdot T^{1.5} \cdot \exp\left(-\Delta E_{\text{band}}/k_B T\right) + A_2 \cdot \exp\left(-\Delta E_{\text{hopp}}/k_B T\right), \]  

(2.1)

where \( T \) is a temperature, \( \Delta E_{\text{band}} \) is band gap energy, \( \Delta E_{\text{hopp}} \) is hopping activation energy, \( k_B \) is Boltzmann constant and \( A_1, A_2 \) are preexponential factors. The band conductance activation energy 0.65 eV is the same for all layers. However, hopping conduction changes severely with either the growth temperature or Be doping. An important is a discussion of the sheet resistance of layers at room temperature (figures 5.3 and 2.14). The highest sheet resistance is observed for material undoped and grown at temperature 250 °C. A lower resistance has material with \( T_g = 220 \) °C and this is a consequence of lower growth temperature in this case 220 °C. Both Be doped layers have significantly lower sheet resistance mainly due to higher hopping conduction, as the analysis of the temperature dependence of resistance implies. The values of preexponential factor \( A_2 \) clearly prove that. Activation energy of hopping process was

![Figure 2.14: Arrhenius plot of the conductance of circular TLM structure on the 1µm thick LT GaAs layer.](image-url)
found to be very similar in all analysed LT GaAs layers and changes within 0.04–0.052 eV. The ratio of the band and hopping conductance $G_{\text{band}}/G_{\text{hopp}}$ in beryllium doped materials is found to be 15 and 12.5 for the sample with $T_g = 250^\circ$C and $T_a = 220^\circ$C, respectively, while undoped materials with $T_g = 220^\circ$C and $T_a = 250^\circ$C exhibit the ratio of 17 and 16, respectively. All values were determined at room temperature.

This results indicates that in Be doping materials the hopping component more dominates as in the undoped samples. From this relatively small influences on the total conduction can be spoken that a conduction properties can be described by band conduction only. This is the fact that with increasing temperature the hopping conductivity decreases more rapidly than the band conductivity.

### 2.1.4 Carrier lifetime in LT GaAs

It is well know that in LT GaAs material is lifetime in comparison to another semiconductor material in subpicosecond range. Figure 2.15 shows review of reached carrier lifetime in published data compared to our values, for different growth temperatures. Lifetime of the photo-generated carriers in LT GaAs was studied using femtosecond time resolved reflectivity measurements. From presented data one can see the shortest carrier lifetime is observed for samples grown near to the grown temperature 250°C. Samples doped with Beryllium indicates shorter carrier lifetime as undoped samples. During LT growth, excess As is incorporated as As antisite point defects AsGa, which are double donors close to the center of the band gap. Less than 10% of the AsGa are

![Figure 2.15: Carrier lifetime as a function of the growth temperature.](image_url)
ionized, As, while the majority is neutral. The concentration of AsGa increases with decreasing growth temperature $T_p$. It is well established that the fast response time of LT GaAs is caused due to carrier trapping into defects, which becomes faster with decreasing of $T_p$. Electrons are trapped into ionized As$_{Ga}^+$. Be dosing results in a much faster decay for $T_p = 250^\circ$C contrary to the decay for $T_p = 220^\circ$C. They recall that the Fermi level is lowered upon acceptor doping, which gives rise to a larger fraction of As and to the formation of doubly charged As for high Be concentration [24].

Consequently, we attribute the faster response for high Be concentration [$10^{19}$ cm$^{-3}$] to enhanced electron trapping due to the larger concentration of ionized antisites. Moreover, we recall that fast trapping is followed by slower recombination of trapped carriers in LT GaAs and that trapping is slowed down due to traps filling at higher carrier densities and longer times. Carrier lifetime less than 200fs can be obtained in annealed LT GaAs grown at 200$^\circ$C$-250^\circ$C as compared to SI GaAs bulk with $\tau_e \approx 1$ ps, as shown in figures 2.16 and 2.17. From these results Be-doped LT GaAs looks like a suitable candidate as a material for fabrication of ultrafast photodetectors and high frequency operating photon mixers in every case. But we observed an very important dependence which looks that for fabrication of our devices we will used only undoped material. As will be presented later in this work we measured response time of very simple photoswitches with pump-probe measurements. Its consists of replaced LT GaAs layer on host substrate with elimination of the influence from the substrate. Details about the fabrication of these devices are describe in Chapter 3. Figures 2.18 and 2.19 shows response time as a function of average electric field calculated from the bias voltage and from the spacing between contacts. In our case the contacts are the part of the coplanar strip-lines. Response time values are higher in both cases in comparison with measured carrier lifetime because of RC constant. Interesting on these figures is the fact, that there is a clear difference in the response time dependence on average electric field for Be-doped materials and for the undoped. For Be-doped

![Figure 2.16: Carrier lifetime of undoped LT GaAs compared with SI GaAs material.](image)

![Figure 2.17: Carrier lifetime of LT GaAs doped with Be.](image)
materials we have unfortunately only data for lower electric fields, but the tendency is clear. The samples were illuminated with 405 nm and 810 nm wavelengths. Be-doped sample indicates strong dependence of response time, which increase rapidly with increasing of electric field. On other hand for undoped material, was not observed this dependence and for the illumination wavelength 810 nm response time is constant in hole range of electric field. It means also that carrier lifetime in undoped LT GaAs material doesn’t depend at illumination wavelengths 810 nm on the external electric field. In all cases we observed that response time for 405 nm illumination is longer then for 810 nm. This could be explain due to the local heating and limited effectiveness of recombination centres due to the ionisation of carrier traps. Also the fact that 405 nm excitation generates a population of hot carriers, well above the GaAs bandgap, this can contribute to the longer time relaxation dynamic in LT GaAs materials.

![Graph](image1)

Figure 2.18: Response time of freestanding LT GaAs switches based on the Be-doped material.

![Graph](image2)

Figure 2.19: Response time of freestanding LT GaAs switches based on undoped material.

### 2.2 Nitrogen implanted GaAs

Ion implantation technique has been employed on GaAs to obtain carrier lifetime in picosecond and even subpicosecond regime. Properties of proton [26], Ar+ [27, 28], As+ [29]–[31], and other ion sources implanted GaAs have been investigated thoroughly. Nitrogen-ion implanted GaAs is relatively new in the family of ion-implanted GaAs materials. The implantation of nitrogen into GaAs was initially done to get diluted ternary semiconductor GaAsN. Optical properties of this new material, such as photoluminescence [32] and N+-induced band-gap reduction [33], have been studied in previous work. It is also noted that high energy N+ implanted GaAs becomes highly resistive after high-temperature annealing [34].
2.2.1 Ion implantation technique

Ion implantation was first applied to semiconductors over 30 years ago as a means of introducing controllable concentrations of n- and p-type dopants at precise depths below the surface. It is now an indispensable process in the manufacture of integrated circuits. Damage introduction during ion irradiation and its removal during thermal annealing step are key issues of current interest.

Today there is most of implantation machines used for ion implantation with maximum energy around 300keV or less. Every of these machines are in principle a linear accelerator, which consist of three basic parts: ion injector, acceleration tube and ion beam lines with target chamber.

Ion injector prepares low energy ions with optimal properties, which are injected into system of acceleration electrodes so called acceleration tube. Ion injector encapsulates ion source, basic beam-shaping system and eventually can include beam separation system. There is a lot of different types of ion sources: penning sources, vF-plasma sources, ECR IS (electron cyclotron resonance ion sources), ion sputtering sources, sources of negatively charged ions (for tandem accelerators) and many more. Beam shaping system is system of electrostatic or magnetic lenses used to shape beam of ions after their extraction from ion source through the extraction electrode. After extraction and basic shaping there are different fractions of ions in beam. These fractions differ in energy, mass and charge state of ions. Therefore it is useful to detach only ions important for us before acceleration. As a separator we can use a magnet or a Wien filter. We can separate desired beam fraction after acceleration too, but high-energy beam needs stronger separation fields.

Ion beam from injector is then accelerated in acceleration tube – a high voltage connected to the system of electrodes that produce gradient of electrostatic potential and force charged particles to increase their kinetic energy and velocity.

After acceleration it is possible to use ion beam directly for implantation. This is the situation for ordinary implantators. In case of scientific accelerators there is target chamber not mounted directly behind acceleration tube but there are few branches of beam-lines and beam is switching to them using bending magnet mounted at the exit from acceleration tube. In this case the target chamber for implantation is placed at one of these beam lines.

For low energy implantation is possible scan with ion beam using electrostatic scanning system and irradiated whole area of sample. For higher energies there are higher fields intensities needed for manipulation with ion beam therefore it is better to manipulate sample itself while beams is static. For whole area implantation there is possibility to defocus ion beam and so implanted large area substrates. Implantation of static sample with static ion beam required a homogenous space distribution of ions in beam.

All parts that share in manipulation and transport of ion beam have to work under high vacuum in order to prevent interaction between beam and residual air atoms. This spurious interaction results in ion beam energetic and space disorder. Individual parts of accelerator are divided with vacuum valves, for protection against unexpected change of pressure in the vacuum system.
Figure 2.20: Schematic layout of the accelerator; 

The preparation of bulk of our samples was performed by the linear 900kV accelerator at the Slovak University of Technology, Bratislava, Slovakia [35]. In figure 2.20 is a simplified scheme of this device. Presently, the ion implantation is performed in a dedicated target chamber located at the low-angle exit of the bending magnet. The low energies are obtained by the de-acceleration technique taking the advantage of ion-optical flexibility of the accelerating tube. The dose is measured by collecting
the charge from the sample with a secondary-electron suppression system.

2.2.2 Properties of Nitrogen implanted GaAs

The aim of this part is to present properties of metal-semiconductor-metal (MSM) photodetectors fabricated on low and high-energy, $N^+$-implanted GaAs and demonstrate the performance improvement of these devices, as compared with those fabricated on low-temperature (LT) grown GaAs. The part of the samples implanted with energy 400 keV was prepared in Research Centre Jülich and samples implanted with energies 500, 700, 880 keV were prepared in a linear, 900-kV accelerator in Bratislava (Slovakia).

It is well known that nitrogen implanted material becomes highly resistive after temperature annealing process. In the figure 2.21 one can see current-voltage characteristics measured on the samples with CPS with contact spacing of 10 $\mu$m, fabricated on the top of 400 keV nitrogen implanted material with dose $1 \times 10^{16}$ ions/cm$^2$ annealed at different temperatures. All samples were measured at the biases up to 100 V. Non-annealed material together with material annealed at 200°C indicate very high dark currents, which initialize breakdown at lower voltages in these materials at average electric field 40 kV/cm. All other samples show that dark current decrease rapidly with increasing of annealed temperature. The difference between non-annealed and sample annealed at 600°C is clear and dark current for annealed sample is more than 4 orders of magnitude lower than for as-implanted material. This could be explained by the re-crystallization process which are initialized during annealing process. Implantation process creates a high number of defects. These increase number of free carriers and the electrical conductivity of those materials is very high. After annealing the concentration of free carriers rapidly decrease and the material becomes high resis-

![Figure 2.21: Current-Voltage characteristics of MSM photodetectors on the non-annealed material compared with materials annealed up to 600°C.](image1)

![Figure 2.22: Current-Voltage characteristics under illumination $\lambda = 850$ nm with input power 70 $\mu$W.](image2)
tive. The situation is similar for measurements of photocurrent, at biases up to 20 V photocurrent decrease with increasing of annealing temperature (see figure 2.22). For samples fabricated on the non-annealed and 200 °C annealed material was not possible to measure the photocurrent, because during illumination total current increased in time also at the constant biases and this process was not possible to stop. In these samples became breakdown earlier approximately at the biases up to 20 V. As will be seen later from TRIM simulations, the concentration profile in nitrogen implanted materials only with one implantation energy is inhomogeneous. This comes from statistical distribution of implanted ions to the material. Figure 2.22 shows characteristics of photocurrent measured up to 100 V bias. At higher biases characteristics change their ohmic character behavior and goes to the quadratic and sublinear dependencies. The mechanism of the current transport in these materials will not be discussed in this work. All these effects could be simple explained through the non homogeneous distribution of nitrogen incorporated ions in GaAs matrix. After implantation are not all implanted ions electrically active. But in the annealed material their also plays role in different distribution of electric field. Characteristics measured without illumination show linear behavior in the large range of bias. This is through the fact that implanted region becomes a barrier, which decreases a collection of carriers from deeper regions, which were not implanted. After illumination increases the concentration of free carriers due to the photogenerated carriers what change distribution of electric field and at the higher biases are collected also carriers from non-implanted regions. This effect is good to see in the figure 2.22 displaying photocurrent characteristic of the sample annealed at 600 °C, photocurrent increase more than 2 orders of magnitude in the range of 30 Volts. Also photoionization effects play a big role and probably contribute to the total photocurrent.

Properties of nitrogen implanted materials with higher implantation energies were studied in the next. MSM structures, with the finger width of 1 μm and finger spacing of 2 μm were patterned on the top of these materials. As to see in the figure 2.23 sample implanted with 880 keV nitrogen ions is highly resistive after implantation process without annealing. Figures 2.25 and 2.27 show that all materials have high electrical conductivity by different implantation energies and doses of nitrogen ions and annealing process is necessary as in the case of 400 keV implanted material. Figures 2.24 and 2.26 show very high responsibility for the some implanted materials. These values could be explained through the photoionization effects and collection of photogenerated carriers, which are collected from non-implanted regions. Figure 2.28 shows the situation after illumination of highly doped nitrogen implanted GaAs material. The situation is comparable with the 400 keV implanted material and with dose 1·10^{16} ions/cm². There was not possible to measure stable photocurrent and from this reason the characteristics for this implanted materials look very chaotic. In this work were not studied in the next properties of the all of these implanted materials. We concern us to the sample implanted with dose 3·10^{15} ions/cm². These materials were not annealed in classical way in rapid annealing process, but with the assistance of laser beam. After illumination, 60 minutes with input power 20 mW at wavelength λ = 850 nm, of the active area of the photodetectors fabricated on this materials, become highly resistive also material implanted with the energy 700 keV. After this laser assisted annealing process
Figure 2.23: Current-Voltage characteristics of MSM structures with active area $100 \times 100 \mu m^2$ and with finger width/spacing $1/3 \mu m$.

Figure 2.24: Current-Voltage characteristics under illumination $\lambda = 850 \text{nm}$ with input power $70 \mu W$.

Figure 2.25: Current-Voltage characteristics.

Figure 2.26: Current-Voltage characteristics under illumination $\lambda = 850 \text{nm}$.

Figure 2.27: Current-Voltage characteristics.

Figure 2.28: Current-Voltage characteristics under illumination $\lambda = 850 \text{nm}$.
samples indicated stable dark currents and photocurrents under lower input power. For response time measurements, which will be presented later we have fabricated MSM structures, with the finger width of 1 μm and finger spacing of 1.5 μm were patterned on the two types of our N⁺-GaAs materials, using conventional photolithography and a lift-off technique. The MSM devices consisted of Ti/Au contacts with thickness of 10/160 nm. Next, the entire surface of our structures, except of the MSM area, was coated with 200 nm of SiO₂ to provide electrical insulation and external Ti/Au coplanar strip (CPS) lines, needed for electrical measurements, were fabricated. For the sake of the performance comparison, several photodetectors with the same MSM geometries were also fabricated on LT-GaAs grown directly on a native GaAs substrates.

Figure 2.29 shows typical current-voltage (I – V) characteristics of both the N⁺-GaAs and LT-GaAs photodetectors measured in the dark at 300 K. The N⁺-GaAs devices exhibit an ohmic dependence up to the voltage bias $V_B \approx 6$ V and a quadratic dependence at higher biases. $V_B$ up to 25 V and 32 V was applied to the 700-keV and 880-keV N⁺-GaAs MSM’s, respectively, with no dielectric breakdown occurring. The rapid increasing of the dark current at higher $V_B$’s for our N⁺-GaAs photodetectors can be explained by collection of carriers in the device deep regions, which were not implanted with N⁺ ions and, as a result, possessed much higher conductivity. The LT-GaAs structures show an ohmic behavior in the whole range of applied $V_B$ (max. 30 V, corresponding to the average electric field of 200 kV/cm). However, their actual dark currents are significantly higher, especially at low $V_B$ (< 10 V), where the best performer, $E_{IMPL} = 880$ keV N⁺-GaAs MSM exhibits the lowest, below 10 nA, dark current.

![Figure 2.29: Dark I-V characteristics of the MSM photodetectors with active area $10 \times 20 \mu m^2$ and with finger width-spacing 1/1.5 μm](image1)

![Figure 2.30: Current responsivity of the three tested MSM photodetectors as a function of the bias voltage under illumination $\lambda = 850$ nm.](image2)

Figure 2.30 presents the current responsivity of our N⁺-GaAs and LT-GaAs photodetectors. In comparison to the LT-GaAs devices, our highly implanted N⁺-GaAs
photodetector exhibited more than two times higher responsivity. At the very high bias, we observed in both of our N⁺-GaAs MSM’s a drastic increase in the responsivity, which, as in the case of the dark current, can be attributed to collection of photo-generated carriers in the deep non-implanted regions of our material. Figure 2.31 shows implantation profiles of N⁺ ions in GaAs, calculated using the transport of ions in matter (TRIM) simulation program [36]. TRIM is the most widely used software to calculate the stopping and the range of ions in matters. For samples implanted with \( E_{\text{TRIM}} = 700 \text{ keV} \) and \( 880 \text{ keV} \), the nitrogen ions reach depths of 1250 and 1400 nm, respectively. Thus in both cases, there is a thin non-implanted layer of n-doped GaAs. This layer is expected to affect the properties of our devices at very high bias voltages, it should not, however, the influence our photoresponse measurements since the penetration depth of 810 nm photons is approximately 1 \( \mu \text{m} \). In future devices, the contribution from the non-implanted region, where the carrier lifetime is much longer, could be minimized by implanting GaAs with higher energies. Also by the implantation with the suitable chosen implantation energies improvement of properties of our devices will be achieved, because with this way we could prepare material with more homogeneous concentration profile in full bulk of the implanted material.

Figure 2.32 shows results from the responsivity measurements on the MSM photodetectors fabricated on the implanted materials. From responsivity measurements we can see that photodetectors have different responsivity and this depends on implantation energies. What is very interesting is a fact that our photodetectors based on the implanted material are highly sensitive also at the shorter wavelengths in contradiction to those presented results on the LTGaAs in figure 2.5. This gives us big chance to produce high speed photodetectors on radiation resistant material for shorter wavelengths. Ultraviolet photodetectors are needed in many applications and today used materials as SiC or GaN can not be concurrence for this material, because of its relatively long carrier lifetime. Of course in this type materials is the mobility much

Figure 2.31: TRIM-simulated profiles of the penetration depth of implanted N⁺ ions into a GaAs film.

Figure 2.32: Responsivity characteristics of the MSM photodetectors fabricated on the nitrogen implanted GaAs.
higher and so it is possible to reach time responses in picosecond range, but these materials degrade earlier after radioactive exposure in comparison to our N-implanted GaAs devices, because of higher atom mass of Gallium and Arsenic, 31 and 33 respectively.

Up to now results presented in this work were only from relatively high energy implanted materials. The reason is that for lower energies we didn’t obtained optimal properties of nitrogen implanted materials, that are necessary for high frequency operating devices. Figure 2.33 shows simulated profiles of the penetration depth of implanted N⁺ ions with energies 82, 140 and 191 keV into an SI GaAs film. Also with 191 keV implantation energy we were not able to reach and with nitrogen ions modified deeper regions than 500 nm. Figure 2.34 presents data for carrier lifetime in low energy nitrogen implanted GaAs (191 keV) compared with SI GaAs and LT GaAs material. It’s clear that implantation process created in the bulk of GaAs defects which could explain ultrafast carrier lifetime. On the other hand the presented data shows that relaxation time in this material consists of minimum two components. Ultrafast component decreases the peak amplitude to 1/e in 130 fs and after this time the characteristic has slow decreasing behavior, what is explains due to the contribution of slow carriers from the deeper non implanted regions. There was initialized process of creating free carriers, when the pump beam with wavelength of 840 nm penetrated to these deeps. Aim of this work is also to find optimal implantation energy, what could be helpful also for industry applications. The process depending with implantation at higher energies is financially and technical exacting. The most of the implantation machines in semiconductor industry are built for accelerating energies up to 200 keV, for double ionized atoms up to 400 keV. With increasing of the ionization of ions, rapidly decreases current density of ion beam and for the same dose but with lower current of ions, increase time of implantation. We also implanted LT GaAs with the same energy and we observed same carrier lifetime as for implanted SI GaAs (see figure 2.35).

Figure 2.33: TRIM-simulated profiles of the penetration depth of implanted N⁺ ions with energies 82, 140 and 191 keV into an SI GaAs film.

Figure 2.34: Carrier lifetime of SI GaAs material compared with undoped LT GaAs material and low energy (191 keV) implanted SI GaAs.
It was about 130 fs. Definitely it was observed that with implantation, we can again decrease carrier lifetime also in LT GaAs and the characteristic dfin’t show any ”shoulder” effects as in the case of implanted SI GaAs. Our measurements on high energy implanted GaAs show (figure 2.36) that after implantation these materials indicate subpicosecond carrier lifetime and as will be presented later photodetectors fabricated on this materials show higher pulse amplitude than LT GaAs devices.

As was spoken earlier, implanted materials become after annealing highly resistive. Annealing process influences relaxation dynamic. Figure 2.37 shows carrier lifetime
in 400 keV N-implanted GaAs at different annealing temperatures. All samples were annealed in nitrogen gas overpressure for the whole time. Temperature was increased to final temperature in 60 seconds and sample was annealed 600 seconds for the final temperature. After annealing process sample was cooled down to R.T. at next 600 seconds. The time-resolved photoresponse waveforms (figure 2.38) of photodetectors fabricated on these implanted materials show similar results as in figure 2.37. From these results we can see that carrier lifetime increase with increasing of annealing temperature. For sample annealed at 600°C carrier lifetime reaches values comparable that previous observed for non-implanted GaAs. These results show that also 400 keV nitrogen implanted GaAs material is not useful for fabrication of ultrafast photodetectors. For our next work we choose material implanted with higher implantation energies, because only this way we can eliminated the influence of the slow carriers from the non-implanted regions. The time-resolved photoresponse waveforms of our photodetectors are shown in figure 2.39. Under the same operating conditions, all our photodetectors exhibit transients with the same, ~2.7-ps full-width-at-half-maximum (FWHM) and the exponential-type falling edge with the decay time ~2 ps. Relatively large FWHM and the exponential pulse decay show that photoresponse dynamics is not limited by the subpicosecond carrier lifetime in either N⁺-GaAs or LT-GaAs, but it corresponds to the parasitic capacitance of the MSM structure. Indeed, the estimated capacitive time constant of our photodetectors is on the order of ~2 ps, in good agreement with the decay time of the transients shown in figure 2.39. We note that superior responsivity of N⁺-GaAs devices translates into their high sensitivity. For \( E_{\text{IMPL}} = 880 \text{ keV} \), the N⁺-GaAs photodetector exhibits the signal peak amplitude almost 2 V, biased at 9 V and illuminated by the incident optical power \( P_N = 10 \text{ mW} \). This amplitude value is more than 50% higher than that for our best LT-GaAs photodetector operated under the same conditions [37]. Figure 2.40 shows the photoresponse...
amplitudes of the three photodetectors as a function of $P_{IN}$ with $V_B = 9\ V$. We observe that all curves start with the linear dependence and gradually approach saturation. As we observed earlier, the $N^+$-GaAs photodetectors exhibit significantly higher the photoresponse amplitude than the LT-GaAs device.
Chapter 3
Technology

Rapid progress in the miniaturization of monolithically integrated electronic circuits is the result of a set of fabrication processes known as a planar technology. In this technology, complex circuits are on the surface of a wafer in a succession of process steps. Such technology was applied also to fabricate an MSM photodetector based on LT GaAs material. In principle all technological steps are the same for all materials, there are only small differences in using different types of photoresists. This, in general, depends on the adhesive interactions between the photoresist and the material which is used for a particular technological process. There are many considerations that should be taken into account during the mask design and finish with the work condition for device. For example, it is very difficult to produce in one layer structures with very different sizes. For this reason more masks are used for fabrication micrometer and sub micrometer sized structures integrated with large contacting pads. As was said there are a lot of small influences on technology and about most important problems in technological process will be spoken in the next parts.

For fabrication of ultrafast photodetectors and photoswitches, as well as, photomixer devices as a source of radiation in THz range, there was used several technological steps. Electrical properties of devices with trenches MSM electrodes are presented in Chapter 5. Annealing process will be discussed also in Chapter 5, dealing with optimization of MSM structures.

In this part will be also presented lift-off technique, which was used for fabrication of freestanding photoconductive switches placed on top of host substrates with higher temperature conductivity, as well as, with higher breakdown voltage. The principle of lift-off technique is well now, but only in this work was first time fabricated devices with assistance of improvement lift-off procedure below micrometer dimensions. This allowed for the first time integration of ultrafast LT GaAs material in hybrid electric circuit as a source of subpicosecond electrical pulses. Very promising material as a host substrate for semiconductor materials is organic polyethylene terephthalate foil we used for its excellent mechanical properties. In future this application could be very perspective in semiconductor industry which will effort erlarge appliance novel electronic paper in communication technique.
3.1 Lithography process

In this work we used conventional optical photolithography and electron beam lithography (EBL) for fabrication of photodetectors and photomixer devices. For fabrication of structures with size under 1 μm there was used only EBL process (figure 3.1). The photolithography process consist of these basic steps:

- Cleaning the wafer surface
- Application of photoresist
- Lithography
- Metallization

3.1.1 Cleaning the wafer surface

Every surface is covered with foreign substances that cause a device failure. From this reason it is necessary to clean the sample before any other process starts. Standard cleaning procedure consists of removing organic particles in acetone and propanol baths. Inorganic particles are removed by rinsing in the deionized water followed by blowing in dry N₂. In many cases O₂ plasma can be used too. It is worth to note, that all such cleaning procedures have to be performed in the clean room compartments with reduced dust content in the air.

3.1.2 Application of photoresist

Typical procedure for photoresist deposition begins with dehydratation of the sample surface at 150°C for 5 minutes, although for better results is possible to use 180°C. This process is extremely important for a good adhesion of photoresist on the sample surface. For very smooth surfaces, a promoter of adhesion is used.

After this step a resist is spun on top of the substrate. The positive photoresist AZ5214 typically at 4000rpm. In this case, the thickness of the resist layer is between 1200–1400 nm and after the spinning sample is put on the hot plate. This step is called prebake of photoresist, also know as softbake, during which liquid-cast resist converts into a solid film. The prebake step involves the physical removal of the casting solvent without degradation of the resist components. In addition, during this step temporary adhesion of the resist is also established. All experiments were carried out on small parts of LT GaAs and the prebake was performed on hot plate typically for 5 minutes at 90°C. Time and temperature are the same also for photoresists AZ5210 and AZ5206.

3.1.3 Lithography

The following step describes an exposure of the sample with photoresist layer. For this purpose a mask-aligner is used. To reach the good contact between the photoresist and the lithography mask, it is necessary to remove the photoresist from the edges of sample. The photoresist layer is always thicker near the samples’ edges. After this
procedure, a typical exposure time of 4.6, 4.0, and 3.6 seconds for resists AZ5214, 5210, and 5206, respectively, result in a stable well defined positive transfer even micrometer-thin features from the mask into photoresist. Values listed above are only approximate and depend on quality of photoresist, intensity and stability of the incident light, and also on developer. Therefore, it is necessary to optimize the lithographical process. After the exposure, photoresist AZ5214 was developed 40–50 seconds in a solution 1:4 of AZ400K. Developing process was interrupted by rinsing a sample in deionized water and sample was dried by pressure sized nitrogen blow.

3.1.4 Metallization

After developing, samples were cleaned in the oxygen plasma for 30 seconds to remove remaines of photoresist. Such surface cleaning procedure preceded the metal deposition to form either MSM finger structures or contacts. The metal multilayer system Ni/AuGe/Ni/Au – 5/90/25/50 (nm) for ohmic contacts and Ti/Au 50/400 (nm) for contact pads was employed. The last step for patterning of metallic layers is the lift-off process in the acetone and propanol baths.

Figure 3.1: SEM micrograph of metallic contacts of MSM structure with finger width 200\(\text{nm}\) and finger spacing 1\(\mu\)m. The metal multilayer system Ti/Au 10/160 nm was employed.
3.2 Wet chemical etching process

For fabrication of MSM structures with trenched electrodes we used basic photolithographic process. In figure 3.2 we show differences between standard and buried contacts’ fabrication. First, although the real distance between contacts is the same, the path over surface is longer. From the technological viewpoint, buried contacts in the form of figure 3.3 require additional lithography to define a groove. To avoid such complication, an anisotropic etching was employed. Using etchant that preferentially etches some crystallographic planes, one can obtain profiles displayed in figure 3.3 For instance, such profiles are found on GaAs when grooves follow [110] and [-110] direction [38]. We made an attempt to verify the potential of our buried contact for the MSM devices. The anisotropic etchant was used [39] resulting in profile shown in figure 3.3 SEM micrograph of such contacts is in figure 3.4 The etch depth was approximately 100 nm. The edges of groove are not parallel to contact metal very probably due to underetching of the used photoresist mask. During the processing, we used photoresists AZ 5206, 5210 and 5214, but for all of them there we observed underetching of the structures.

Next, we used electron beam resist PMMA 200 and 600. Figure 3.5 shows buried contacts fabricated with assistance of PMMA photoresist mask. We observed that these resists are resistant to both acid solutions up to 300 seconds. Thus, using these solutions:

$$\text{H}_2\text{SO}_4 : \text{H}_2\text{O}_2 : \text{H}_2\text{O} (1:1:50)\text{ and \ H}_3\text{PO}_4 : \text{H}_2\text{O}_2 : \text{H}_2\text{O} (3:1:50)$$

It is possible to etch LT GaAs material in the rate 60 nm/min and 100 nm/min in H$_2$SO$_4$ and H$_3$PO$_4$ solution, respectively.

![Principle comparison between standard contacts and buried contacts.](image1)

*Figure 3.2: Principle comparison between standard contacts and buried contacts.*

![Shape of groove when a selective etching is used.](image2)

*Figure 3.3: Shape of groove when a selective etching is used.*
3.2. WET CHEMICAL ETCHING PROCESS

Figure 3.4: SEM micrograph of buried contacts of MSM structure. For wet etching process was used AZ 5214 photoresist mask.

Figure 3.5: SEM micrograph of optimized buried contacts of MSM structure. For wet etching process was used PMMA 600 photoresist mask.
3.3 Ion Beam etching

Another way to enhance the electrical parameters of MSM structures is to fabricate buried contacts with an assistance of argon ion beam etching process. Efficiency of the process depends on the target material, atom density as well as atomic mass of atoms of the accelerating beam used for etching. In this case we used Ar ions for etching. As an etching mask it is possible to use, again, a photoresist. In our case we used both AZ5214 which is, as well as, PMMA 600 resists. The critical parameter is only the etching time. In GaAs, etching usually takes 1 hour for 300 nm at accelerating voltage 250 V and 50 mA of ion beam current. After this time there is possible to use a photoresist mask for metallization process without any problem. But if it is necessary make a structure in deeper regions of material, etching time is long lift-off is complicated due to resist hardening. In figure 3.6 we can see that during IBE process the removed material is redeposit on the resist walls near the contact. This is from practical reason not negative effect only for design. As will be seen in Chapter 5, the buried contacts show, despite of these lithographical imperfections an excellent electrical properties. Figure 3.7 shows a detail of the buried contact with the view on the redeposit LT GaAs walls. The material's break down voltage does not decrease as it will be seen later.

![Figure 3.6: SEM micrograph of buried contacts of MSM structure. For IBE etching process was used PMMA 600 photoresist mask.](image1)

![Figure 3.7: SEM micrograph of the detail of buried contacts created by assistance of IBE. The detail shows walls created from redeposit LT GaAs.](image2)

3.4 LT GaAs lift-off technique

As it was first reported by Yablonovitch et al. [40, 41], the AlAs grown under the LT-GaAs film enables selective AlAs chemical etching and results in epitaxial lift-off of the LT-GaAs layer. This procedure allows for the freestanding LT-GaAs film to be removed from the native GaAs substrate and transferred on top of a variety of nonepitaxial substrates for material and device characterization [41, 42]. Bonding between the LT-
GaAs and the new substrate surface is established through the intermolecular Van der Waals force. Excellent adhesion and durability of the freestanding LT-GaAs was demonstrated by device patterning both before [43] and after [44] the film transfer on top of sapphire or glass substrates. We must stress, however, that for successful LT-GaAs integration into practical electronic or optoelectronic circuits, we need not only a robust technique for a reliable LT-GaAs lift off, transfer, and bonding, but also the size of the transferred structure must be microscopic, comparable with the size of circuits’ components.

Our devices were fabricated using molecular beam epitaxy. We started with a 300-nm-thick layer of AlAs on top of the GaAs substrate, followed by a 500-nm- to 1.5-μm-thick LT-GaAs film grown in the temperature range 200°C to 250°C. The AlAs/LT-GaAs bilayer was subsequently patterned by photolithography and ion-beam etching to form a set of LT-GaAs microswitches, featuring sizes from 10 μm × 10μm to 150μm × 150μm. The LT-GaAs devices were next lifted from the GaAs substrate by selective chemical etching of the AlAs layer in the diluted HF solution (HF:H₂O/1:9). After cleaning in de-ionized water, a selected microswitch was transferred on top of a chosen substrate using metallic tip, electrostatically charged and electrically isolated from the ground. To minimize height difference between the switch and the substrate surfaces, our substrates contained 500-nm-deep, ion-etched 'wells' pre-positioned at the designated microswitch spots. Following the microswitch transfer, continuous coplanar strip (CPS) transmission lines crossing our devices were fabricated using Ti/Au deposition and a standard lift-off technique. The principle of lift-off technique shows figure 3.8. A micrograph of one of our devices is shown in figure 3.9.

**Figure 3.8: The principle of LT GaAs lift-off technique.**

LT GaAs layer with thickness of 1 μm was replaced on the top of a coplanar transmission line (CPS). Electrical measurements show good results, but adhesion of LT GaAs layer to the metallic layer is very weak and the structure is mechanically unstable. Figure 3.10 shows photograph of LT GaAs switch, placed at a predefined position into an
etched 'well' and, later, contacted with metallic leads of the CPS, to establish good electrical and mechanical contact. From practical reasons the latter fabrication technique was chosen for preparation of all our switches.

**Figure 3.9:** Thin layer (1 μm) of LT-GaAs fabricated at growth temperature $T_G = 250^\circ$C. The film was lifted-off the GaAs substrate and subsequently bonded to CPS.

**Figure 3.10:** Thin layer (1 μm) of LT-GaAs was replaced to the pre-positioned wells in host substrate and then was done lithography which created CPS above the part of LT GaAs film.
Chapter 4

Measurements

For material characterization and investigation of properties of LT GaAs and nitrogen-implanted GaAs layer, as well as for characterization of photodetectors, photoswitches and photonizers we used two basic measurements techniques. First, electro-optic sampling measurements was used to measure ultrafast photoresponse in freestanding LT GaAs photoconductive switches for the first time fabricated as few micrometer size structures placed on top of host substrates with different physical, electrical and mechanical properties. These measurements were done in cooperation with University of Rochester as well as in Research Centre Jülich.

Photonizers with single dipole antennas and with broadband logarithmic spiral antennas were measured in experimental setup in Max-Plank Institute for Radioastronomy in Bonn. Traveling wave photonizers were measured in cooperation with University of Köln. Additional DC measurement in the dark and under illumination at room temperature, as well as, at temperatures up to 500 K were done in Institute of Thin Film and Interfaces in Jülich.

4.1 Electro-optic sampling measurements

Figure 4.1 shows a schematic of our EO sampling system. This system is based on a mode-locked femtosecond Ti: sapphire laser pumped by an Ar+ laser operating on all lines in the visible at 12.5 W in a TEM00 mode. The output power from Tsunami is about 2.1 W at 810 nm wavelength, the pulse width is about 100fs, and repetition rate is 82 MHz. The wavelength tuning range is between 750 nm and 850 nm. The pulse train from the Ti:sapphire laser is split by a 30/70 beam splitter into two beams: a switching (excitation) beam and a sampling beam. The switching beam is modulated by an acoustic-optic modulator operating at 1 MHz and then focused (if needed for UV light generation) on a BaB2O4 (BBO) crystal, which is a high efficiency frequency-doubling crystal. The switching beam is then guided to illuminate the photoconductive switch to generate an electrical signal. The switching beam can either pass through the EO probe and then illuminate the switch or it can excite the switch directly. In the former case, we can place the switching beam spot and sampling beam spot as close as 50 μm apart and measure close-to intrinsic response determined by the material by eliminating the signal distortion caused by the propagation effect. The second
beam, the sampling beam, travels through a computer controlled optical delay line, a polarizer, a half-wave plate, and is guided by a 10×, long working distance (49.5 mm), microscope objective to a total-internal-reflection (TIR) LiTaO₃ probe, which is placed on the top of the measurement position of the device under test (DUT). The incident light wave polarization should be 45° with respect to z-axis and, in our system the half wave plate is used to rotate the polarization until the optimal alignment is reached. The penetrating electric field along z-axis changes the birefringence of the LiTaO₃. The probing beam is totally internally reflected by the probe, and picks up the information about the electrical signal of DUT. This information is encoded in the change in the sampling beam polarization and then decoded by a polarization analyzer. The polarizer, TIR probe, and the analyzer together form an EO modulator in reflection geometry (see figure 4.1). The compensator placed before the analyzer is used to set the linear operation point of the EO modulator at π/2, where the setup sensitivity is highest. The sampling beam is eventually collected by low-noise photodiodes, and the light signal is converted to an electrical signal. The 1 MHz modulated signal is sent to a mixer, where it is down converted to 255 KHz, and detected by audio lock-in amplifier. The measurement has a sampling character, thus, by adjusting the relative delay between the sampling beam path and the switching beam path, the complete signal of the DUT is mapped out.

![Diagram of EO sampling system with TIR LiTaO₃ probe](image)

Figure 4.1: Schematics of EO sampling system with TIR LiTaO₃ probe.

### 4.2 Photomixing measurements

Figure 4.2 shows the measurements setup for photomixer testing. Two fully tunable semiconductor Lasers (Velocity 6312) are coupled to an optical amplifier TauOptics (TA
Part of the amplifier output signal is monitored by a wavemeter to measure the difference frequency between the two lasers and the rest is chopped and coupled to a monomode fiber optic. The relative position between fiber and active area is controlled by a piezo positioner with a precision of hundreds of nanometers (figure 4.3). This allows us to create a spot size which coincides with the active area of the photomixer.

The photomixer is glued to a silicon hyperhemispherical lens in order to get rid of the surface modes. At the same time the high dielectric constant (12.8) forces the electromagnetic signal radiated by the antenna mostly to propagate in the silicon substrate direction. The chopping of the signal allows lock-in (EG&G 7200) detection of the Golay cell (QMC Instruments Ltd (OAD-7)) signal.

![Figure 4.2: Measurements setup for photomixing [MHJR Bonn]](image)

### 4.3 Characterization of ohmic contacts

The method of determining the specific contact resistance $\rho_C$ and other related parameters is the method of transfer length called the Transmission Line Model (TLM) [45]. In the particular approach a linear array of contacts is fabricated with various spacing between them (see figure 4.4.a). The total resistance between two contacts is measured, the current flow between two contacts illustrates figure 4.5.

Total (measured) resistance $R_{H}$ for square patterns is given by equation:
Figure 4.3: Piezo positional system with a precision of hundreds of nanometers with photomixer block [MPIFR Born].

\[ R_M = 2 \frac{R_K}{w} + d \frac{R_S}{w}, \]

(4.1)

where \( R_K \) is the contact resistance given in \( \Omega \)um, \( R_S \) is the sheet resistance of the semiconductor given in \( \Omega \)square, \( d \) is the spacing between two contacts, and \( w \) is the width of the contact. The value of the specific contact resistance can be obtained from the equation

\[ \rho_C = \frac{R_K^2}{R_S} \quad [\Omega \text{cm}^2] \]

(4.2)

while \( R_K \) and \( R_S \) are evaluated from the \( R_M \) vs. \( d \) plot by linear approximation and the transfer length is given by:

\[ L_T = \frac{R_K}{R_S}. \]

(4.3)

In the rectangular contacts the current flow at the contact edges significantly affects the resulting contact resistance measurement unless mesa structures are fabricated in order to eliminate the unwanted current flow patterns. Circular patterns can be used to avoid the use of mesa structures, because in this type of contacts there is no current flow at the edge. The circular shaped patterns are shown in figure 4.4.b. This enhanced model is called Circular Transmission Line Model. To obtain values of \( R_K \) and \( R_S \) from the CLM model following equation is valid [46]:

\[ R_M = R_S \frac{1}{2\pi} \ln \frac{r}{r-d} + R_K \frac{1}{2\pi} \left( \frac{1}{r} + \frac{1}{r-d} \right), \]

(4.4)

where \( r \) is outer diameter and \( d \) is spacing between the circular structures.
Figure 4.4: Structure for measuring the contact parameters using TLM (a) and CTLM (b) methods.

Figure 4.5: Current flow between two contacts of TLM structure.
Chapter 5

Photodetectors and photoswitches

In this part results from optimization of MSM structures will be presented. Crucial in the fabrication of MSM structures is the right choice of metals evaporated on the surface of photoconductive material. Metal-semiconductor contacts play an important role in determining the electrical characteristics of homogenous semiconductors and semiconductor devices. Contacts in semiconductor devices and integrated circuits can are generally classified in two main classes. There are low-resistive contacts also loosely defined in semiconductor technology as “ohmic” contacts, and Schottky contacts. Different properties of both types of contacts affect device performance. The ohmic contact exhibits an linear $I - V$ characteristic regardless of the polarity of the external applied voltage. Ideally, an ohmic contact has a linear current-voltage characteristic and a very low resistance negligible compared to the resistance of the active region of the semiconductor device. An ohmic contact to an n-type semiconductor should also ideally be made applying a metal with lower work function than is an electron affinity of semiconductor. On the other hand, Schottky barrier contact exhibits an asymmetrical current–voltage characteristic by changing the polarity of bias voltage applied to metal-semiconductor contact is changed. It means a rectifying type of contact. LT GaAs is well now for its high sheet resistance. Because of this, it is difficult to speak in this case about Schottky and ohmic contacts. As will be shown later, both types of contacts show similar characteristics in current–voltage measurements. This is initialized due to a high sheet resistance, the hole-electric circuit consist quasi from two opposite connected diodes with big resistance between them in series. The total resistance in this electrical circuit is very high and after applying an bias in circuit occurs current flow, which has ohmic behavior on the bias, at lower biases. The situation is different at higher biases and will be discussed later in this chapter.

Optimal MSM contact geometry is necessary carefully to choose based to concrete applications, because of $RC$ constant limitation of time response of photodetector devices as will be discussed in this part of the work. Contact geometry play also role in breakdown characteristics of MSM structure and in the end efficiency of collection of photogenerated carriers depends on these geometrical factors. This is theoretically predicted in Chapter 1.

Big influence on electrical properties of prepared MSM structures has the quality of semiconductor surface. Influence of the material factor was discussed in Chapter 2,
presented were photodetectors based on modified GaAs, implanted with nitrogen ions in large range of implanted energies and doses. Buried contacts were first time presented in technological part in Chapter 3. This novel type of contacts rapidly increase of sensitivity of photodetectors and decrease response time. In this case collected carriers from deeper regions because of contacts recession in the material.

Fabrication of structures with replaced active LT GaAs layer on host substrates with different physical and mechanical properties in comparison with native semi-insulating substrate, help us characterize properties of LT GaAs materials (see Chapter 2), but with assistance of improvement Lift-off technique were prepared novel ultrafast photodetectors and photoswitches with micrometer size, which will be helpful in many Optoelectronic applications.

On the base of these improvements were optimized photomixer devices, what will presented in Chapter 6.

5.1 MSM contact metallization

Following three major approaches are used to create good ohmic contacts to semiconductors:

- A low- resistance symmetrical contact to semiconductor is obtained if the barrier height is small compared to $kT$. It is the case when carriers can flow over the barrier in either direction without any limitation.

- One other possibility is to introduce a sufficient large number of recombination centers at the metal-semiconductor interface. In this case metal is deposited on a damaged surface, electron-hole recombination in the depletion region dominates the current transport and the contact presents low resistance to the current flow.

- To increase the doping level at the surface in order to reduce the thickness of a depletion region of the contact.

Basic task is to determine optimal contact to LT GaAs layers. For these purposes the samples with circular TLM structures were prepared. Circular TLM structures are designed for analysis of contact resistance and require simpler technology to fabricate standard TLM structures [46]. We used multilayer metal system Ni/AuGe/Ni/Au applied as a standard for n-type as well as Si GaAs to form ohmic contacts on LT GaAs. All results connected to specific contact resistance and sheet resistance were obtained for measurement on 7 circular TLM patterns with various distance between contacts (see Chapter 4 part 4.3).

We studied the influences of annealing time and temperature on the contacts resistance. The figure 5.1 shows the annealing temperature dependence of the specific contact resistance obtained for material 6157 grown at 200 °C. The annealing time is 90 seconds. It is clearly seen a tendency that contact resistances are lower after annealing in all cases. The lowest specific contact resistance was measured after annealing at 430 °C which well correlates with the published data [47]. The best results of specific
contact resistance reached values of $8.5 \times 10^{-1} \Omega \text{cm}^2$ in comparison to $5 \times 10^2 \Omega \text{cm}^2$ measured before annealing. For LT GaAs grown at 200°C the value of $7.0 \times 10^{-1} \Omega \text{cm}^2$ was previously reported [48]. We tested also an impact of the annealing time to contact resistance. We performed a series of annealing experiments at 430°C with soak time from 30 to 600 seconds. The current-voltage characteristics were not linear except of samples annealed for 90 seconds.

The results are good but checking of the surface of contacts was found that during temperature annealing had to contacts tendencies change, also observed in published data [49]. On the surface of the contacts lines because this parts are on the MSM photodetector most important the gold coagulates creates. May be from this reason the contacts during incidence of light more quickly degrade, but the influence of annealing on the quality of the contacts, which represent contact resistant is without precedence. No negative changes of the electrical performances to the optical and electrical properties of the photodetectors were observed. The creation of gold coagulates occurs between the last gold layer and the eutectical alloy is only 25 nm Ni. From this reason an experiment with the metal system same like early described, but with change that between second nickel layer and the gold top layer is 50 nm Ti was made. In this constellation was after annealing the surface of finger structures more homogenous and without any bump of gold, after CLM measurements was results compared with the first metal system, but in contact resistance does not change very well. The primary factor of these problems is an eutectical layer AuGe which is necessary because from this layer are diffused Ge atoms and these decreases the contact barrier. Generally can be said that the including of the titan layer positively influenced the technological processing of finger MSM structures. The optimal annealing conditions found for material with $T_g = 200^\circ \text{C}$ are subsequently applied to form contact onto layers with $T_g = 220^\circ \text{C} - 250^\circ \text{C}$.

![Figure 5.1](image_url)

**Figure 5.1:** The values of specific resistance at various annealing temperatures for 2µm thick active LT GaAs layer growth at temperature 300°C.

The figure 5.2 shows an specific contact resistance observed for particular LT GaAs layers. From the figure 5.2 one can see that the lowest specific contact resistance was obtained for Be doped material. Primary the reason of the utilization of Be doping of LT-GaAs is connected with expected shortening of the lifetime of photogenerated charge carriers, but here an impact of Be doping on the decreasing of specific contact
resistance is shown. On the samples which are doped with beryllium in the concentration of $10^{15}$ cm$^{-3}$ fabricated contacts have specific contact resistance $1.7 \times 10^{-2}$ and $7.0 \times 10^{-3}$ Ωcm$^{2}$ for material grown at 220 and 250°C, respectively. These values are more than two order in magnitude lower then specific contact resistance on counterpart LT GaAs layers without Be doping. From the figure 5.2 is clearly seen that on the material grown at 250°C contact resistance is higher then for material grown at 220°C. But for a Be-doped layers this tendency is just opposite. To explain this result a detailed analysis of additional experiments in the future is required. The question for the future experiments is to further verify an influence of the different concentration of Be dopants for a quality of the ohmic contact. From this case is very clearly shown that finally values of the ohmic and sheet resistances are lower than in the cases of undoped material. Finally, an impact on distribution of electrical field in the MSM structure has to be evaluated. There are several reasons for a doping of LT GaAs – to help formation of arsenic precipitates [50], to increase ionization ratio of As$_{Ga}$. For 200°C material it was published [51] that concentration of native deep donor and acceptors is $N_D = 10^{16}$ and $N_A = 10^{15}$ cm$^{-3}$, respectively, so that Be concentrations of greater $10^{19}$ cm$^{-3}$ would be necessary before free carriers could be seen. For 300°C material [52] one have established that $N_D = 3 \times 10^{18}$ cm$^{-3}$ and $N_A = 1 \times 10^{17}$ cm$^{-3}$, suggesting that doping level of $3 \times 10^{17}$ cm$^{-3}$ for Be would be required for activation. The formation of As precipitates, which can form a spherical Schottky barriers and attract free electrons and holes also may be inconsistent with fact that Be doped, 300°C MBE GaAs has no electrical activation as grown, but good after activation by 600°C anneal [53].

Figure 5.2: The values of a specific contact resistance for a different materials.

In our case annealing temperature was also 600°C, the temperature at which the precipitates should be formed. The above mechanisms for doping inefficiency in LT GaAs certainly do not exhaust all possible reasons for this phenomenon. It was observed impurity – defect complexes [54, 55] could also render the dopant inactive. It is worth to note that the reality is not absolutely understood and more investigations are needed to be carried out [13]. Figure 5.3 shows sheet resistance for different materials. This parameter has an influence on the character of behavior of dark currents and responsivity characteristics as to see in figures 5.4 and 5.5. Current-voltage characteristics measured without illumination show nearly the same dark currents for different metallization. As was spoken earlier this from high sheet resistance. But for collecting
of photogenerated carriers this plays a big role. Samples illuminated with CW laser illumination indicates for Ni/AuGe/Ni/Au layer system more than 80% higher responsivity values in the comparison with another. The effect of this metallization is clear for results from pump-probe measurements which shows figure 5.5. Photoresponse amplitude for MSM photodetector with an ohmic contact metallization scheme is more than 3 times higher, then for structure with Schottky contacts. This excellent result, gives high peak amplitude at so low bias voltage not observed up to now in any publication. In this case created signal has amplitude is nearly 50% of bias. The both

Figure 5.4: Current-voltage characteristics of MSM photodetectors fabricated on LT GaAs material growth at 250°C. LT GaAs with thickness 1.5µm is grown on 300 nm AlAs interlayer.

Figure 5.5: Responsivity characteristics measured on the MSM photodetectors with 128µm² active area and with finger width/spacing 1/1.5µm. Structures were illuminated at wavelength 850 nm, with input power 160µW.
signals have a FWHM very similar and its about 2.5 ps and this value is due to the RC constant limitation. Figure 5.7 shows photoresponse amplitudes of the photoresponse transients as a function of the input power compared for MSM structures with ohmic and Schottky contacts at bias 9 V, there is more than 150% difference for the structure with ohmic contacts and with no observed saturation of peak amplitudes as in the case of structure with Schottky contacts. Concerning of these excellent results photomixers with improved contacts based on LT GaAs were fabricated (Chapter 6.).

![Graph](image)

Figure 5.6: Comparison of transient photoresponse signals of MSM photodetectors with ohmic and Schottky metallization. The structures are illuminated with input power 12 mW at bias 9 V.

### 5.2 Recessed contacts

In all published data dealing with the LT GaAs and the MSM photodetector structures usually contacts were fabricated on the surface of the material. In this work recessed contacts are introduced and their advantages with comparison to the standard contacts are presented. Standard planar contact exhibits problems with non-uniform distribution of the electric field in an active layer of the MSM photodetector, and with breakdown over device surface. The main idea behind these new contacts is to modify the surface between contacts and to partially bury contacts into active layer. Such approach could help to increase performance of the MSM interdigitated structure. This approach was recently presented in a form of trench electrodes [56]. According
5.2. RECESSED CONTACTS

Figure 5.7: Photoresponse amplitudes of the photoresponse transients as a function of the input power compared for MSM structures with ohmic and Schottky contacts at bias 9 V.

Figure 5.8: Dark current measurements of MSM structures on the material LT GaAs with \( T_0 = 250 \) °C, finger width/spacing 1/2 \( \mu m \) and with active area 50×50 \( \mu m^2 \).

Figure 5.9: Detail of the breakdown voltage measurements of MSM structures on the material LT GaAs with \( T_0 = 250 \) °C.
Figure 5.10: Current-voltage characteristic measurements of MSM structures on the Be-doped LT GaAs with $T_2 = 250 \degree C$, fingers width $w = 2 \mu m$, $L = 3 \mu m$ and with active area $100 \times 100 \mu m^2$ for different recession of the MSM contacts.

Figure 5.11: Responsivity characteristics measured on the MSM under illumination at wavelength 850 nm with input power $100 \mu W$.

to our opinion, there is no doubt in a perspective in utilising so called buried contacts that will be discussed in detail in following paragraphs. Mentioned previously, the breakdown in the MSM device is connected with a surface conditions and edge effect of electrode. Both depends on properties of material and technology of surface passivation. A combination of the electrically passivating layer with antireflection coating could be a solution of this problem. Another possibility relates on physical modifying of surface between electrodes to increase the breakdown voltage of MSM device and modify electric field distribution therein. Figures 3.2 and 3.3 in the Chapter 3 there are showed differences between standard and buried contacts. First, although the real distance between contacts is same, the path over surface is longer. Figures 5.8 and 5.9 show this effect on the current-voltage characteristics of standard MSM structure and with modified contacts. As is to see from the figure 5.9. Structure with recessed contacts occures more then 20% higher breakdown voltage. At lower biases dark current is in hole range of bias for recessed contacts higher. To explain the observed increase of dark current, several causes were considered. The increased dark current with recessed depth would be caused by the increased overlap area of the electrode and bulk LT GaAs, and the trap assisted generation at the side walls of the grooves due to damages caused by the chemical etching. Increasing of breakdown voltage is than a function of the recessing of contacts. Figures 5.10 and 5.11 show the current-voltage characteristics for MSM structures with different depth of recession of contacts in the range from $-20 \text{ nm}$ to $-300 \text{ nm}$. From the figure 5.10 one can see that for contacts recessed up to $100 \text{ nm}$, dark current increases and for recession deeper then $180 \text{ nm}$ dark current decrease. Situation is similar for photocurrents measurements. Figures 5.12 and
5.13 show the dark current and responsivity dependence as a function of contacts recess depth. One can see that for both dependencies there are maximum of dark current and photocurrent. Maximum of dark current was measured for structure recessed 20 nm and for deeper recess these values decrease. Maximal photocurrent was collected from the structures with contacts recessed approximately 180 nm. It appeared that the recessed electrodes collect the photogenerated carriers better, and hence an increase in the photocurrent was observed. However, when the recessed depth is about 180 nm the deeper carriers might be collected totally, and photocurrent saturates. For contacts recessed deeper total efficiency of collecting of photogenerated carriers decrease because decrease electric field on the surface, which can collect photogenerated carriers on the surface. Of course for different materials will be optimum for deep recession in different depth. This is due to the fact that distribution of the electric field depends on the sheet resistance of the material. Figures 5.14 and 5.15 show the difference between Be-doped material growth at 210 °C and 250 °C. As was spoken in Chapter 2 part 2.1.3 growth temperature has influence on the conductivity of the layers. From this reason so big difference in the same MSM geometry and the depth recession of contacts for different materials is observed. From figure 5.14 one see, that for material growth at 250 °C dark current for deeper recession decreases but this result is in contradiction to measurements on the material growth at 210 °C, where with deeper recession increase dark current. This effect could be explained theoretically, and this phenomenon will be studied in more details in the future.

Not all results from current-voltage measurements are so clear as presented in figure 5.8. Samples fabricated on the LT GaAs material with Bragg mirror (16044) show up to 40 V bias similar values of dark current, only for higher biases values for non-recessed sample are higher (see inset in the figure 5.16). This indicates to overheating effects, these are also connected with lower efficiency of collection of photogenerated carriers at higher biases (see figure 5.17). Figure 5.17 shows more than 40% difference in values of the responsivity at 60 V bias. For lower biases this difference is lower,
Figure 5.14: Current-voltage characteristic measurements of MSM structures on the Be-doped LTGaAs with \( T_\text{g} = 250^\circ \text{C} \) (13167) and with \( T_\text{g} = 210^\circ \text{C} \) (13183). Finger width/spacing is 1.5/2.5\( \mu \text{m} \) and with active area 100\( \times \)100\( \mu \text{m}^2 \).

Figure 5.15: Responsivity characteristics measured on the MSM under illumination at wavelength 850 nm with input power 130\( \mu \text{W} \).

Figure 5.16: Dark current measurements of MSM structures on the material LTGaAs (16044) include Bragg mirror with \( T_\text{g} = 230^\circ \text{C} \), finger width/spacing 1/2\( \mu \text{m} \) and with active area 100\( \times \)100\( \mu \text{m}^2 \).

Figure 5.17: Responsivity characteristics measured on the MSM structures with surface and wet etch recessed (buried) contacts under illumination at wavelength 850 nm with input power 160\( \mu \text{W} \).

but as will be presented later, higher responsivity values indicate also higher peak amplitudes from EO sampling measurements. By electro-optic sampling measurements
we observed for MSM photodetectors with different buried contacts higher peaks amplitudes as for structures with contacts on the surface. Figure 5.18 illustrates the transient response measured by the pump-probe method for the MSM photodetectors based on the LT GaAs with buried contacts compared with non-recessed contacts. The FWHM (full width at half maximum), rise time and fall time for a samples with recessed contacts are better than for the sample with standard contacts. Sample with recessed contacts has for an area of 128 $\mu$m² the value FWHM of 1.0 ps, rise-time of 1.1 ps and fall-time again of 1.1 ps, while sample with standard contacts gives at the same experimental conditions 1.4 ps, more than 5 ps and 2.7 ps for FWHM, rise- and fall-times, respectively. These results could be understood as the deep recession of the buried contacts in the MSM structure produces higher lateral electric field fall-time decreases. All these structures the RC constants are limited. Contacts with 100 nm deep recess was observed that they do not contribute significantly to the increase of the geometrical capacitance of the MSM structure. In this case contacts were prepared with chemical wet etching process described in Chapter 3. This is well presented in the figure 5.19. Measured values of capacitance of standard MSM detectors and detectors with buried contacts for five various MSM areas do not differ more than 10%. The systematic difference between measured and calculated capacitances of the MSM structures is caused due to parasitic capacitance from contact pads.

Theoretical values are calculated using the formula 1.2 from the Chapter 1. As to see from figures 5.20 and 5.21 peak amplitudes increased more progressive with an applied bias in comparison with contacts fabricated on the surface. Also response time is in whole range of bias shorter for structures with recessed contacts, which shows for an improvement of electrical properties of this type of contacts. It could be said that response time is for all samples it means with surface or recessed contacts constant
Figure 5.20: Amplitudes of the photoresponse transients as a function of the bias voltage compared for MSM structures with Schottky contacts illuminated at 810 nm wavelength with input power 1 mW.

Figure 5.21: Response time as a function of bias voltage for 1 mW input power compared for MSM structures with contacts fabricated on the surface and 100 nm recessed in the bulk of LT GaAs material.

in hole range of bias or input power (see figure 5.23). This fact is connected with material property. In this case LT GaAs layer lies on the Brogg mirror (see Chapter 2), which from the optical reason improves also electrical isolation from the substrate. This works as a barrier for slow carriers which could be collected from the substrate at higher biases. Figure 5.22 shows photoresponse amplitudes without saturation even with increasing of input power for structures with recessed contacts in contradiction to the surface contacts. The highest peak amplitude observed for recessed contacts is more than 40% higher in comparison with structure with non-recessed contacts. Also figures 5.21 and 5.23 show that response time obtained from the amplitude drops to its 1/e value, for MSM structures with recessed contacts is about 0.5–0.7 ps in contradiction to structures with non-recessed contacts there were obtained values of response time in the range 2.1–3.1 ps.

Next improvement of electrical properties of structures with recessed contacts was achieved with using of ion beam etching process (for details see Chapter 3). As to see from figures 3.6 and 3.7 the IBE process is still not fully optimized and needs to be improved in the future, but through these technological difficulties there was obtained increasing of sensitivity of photodetectors fabricated with this type of recessed contacts. Figure 5.24 shows that contacts recessed with assistance of IBE technique exhibit more than one order of magnitude higher dark currents in comparison to non-recessed contacts. All three curves for recessed contacts reach approximately same values of dark current. From responsivity characteristics in figure 5.25 we can see, that all three curves has similar behavior of responsivity characteristics. This tendency is strong different for low biases up to 5 V, which indicate different efficiency in collection of the created carriers in the regions near to the surface of semiconductor. These curves show
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Figure 5.22: Photocurrent amplitudes of the photoresponse transients as a function of the input power at 9 V bias, compared for MSM structures with surface and wet-recessed Schottky contacts.

Figure 5.23: Response time as a function of input power at 9 V bias. Structures were illuminated with 100-fs-wide optical pulses at wavelength 810 nm.

Figure 5.24: Dark current measurements of MSM structures on the material LT GaAs (16044) include Bragg mirror with $T_0 = 230^\circ$ C, finger width/spacing $1/2\mu m$ and with active area $100\times100\mu m^2$.

Figure 5.25: Responsivity characteristics measured on the MSM structures with surface and dry etch recessed (buried) contacts under illumination at wavelength 850 nm with input power 160 $\mu$W.

complicated behavior of responsivity characteristics up to 10 V. There was observed that the highest photorepons signal (see figures 5.26 and 5.27) produces sample with contact recess depth of 100 nm, and for deeper recession signal decreases. But signal is still more than two times higher in comparison with reference sample with non-
recessed contacts (see figure 5.18). All three samples show that signal FWHM decrease, with recessing of contacts and this is in very good agreement with expectation, that this geometry collects photogenerated carriers faster, because electrodes are nearer to carriers which are deeper in bulk of the photoconductive material.

These results show that for optimization of electrical properties of recessed contacts, also called buried, the compromise between the maximal sensitivity of photodetector and the width of the electrical pulse created from incident optical pulses could be done. As was shown in this Chapter, the optimal recession depth of contacts is different for different materials.

### 5.3 Photoswitches on host substrates

The use of semiconductor photoconductive (PC) devices to detect femtosecond optical pulses and generate picosecond and subpicosecond electrical transients has been the subject of intense research for the last two decades, primarily motivated by the fast growing demand from the optical communication community for ultrafast integrated photoswitches and photodetectors [57]–[70]. There are three basic mechanisms taking part to generation of ultrashort electrical signals by PC devices. The first one and also the cheapest method, due to its independence on the PC material and only the conventional photolithography requirement, is illumination of a semiconductor near its interface with the metal electrode (edge illumination) [71, 72]. The resulting signals have subpicosecond durations, but, unfortunately, they usually exhibit poor reproducibility, since the magnitude of the photoresponse in this case is extremely sensitive to the illumination conditions. The second mechanism relies on a very short time-of-flight
of photo-induced carriers across ultrashort-spaced electrodes. A large family of metal-semiconductor-metal (MSM) diodes with the submicrometer finger spacing and width have been developed and commercially implemented. Generally speaking, generation of ultrashort electrical signals using MSM diodes is also material independent and the devices based on Si [65, 69], GaAs [70], Si-on-Sapphire [65] and InP [73] have been demonstrated to generate picosecond and subpicosecond electrical transients. MSM devices, however, often require implementation of advanced nanometer-scale fabrication techniques and they can be very easily electrostatically damaged. Finally, ultrashort electrical pulses are being generated by simple PC switches, fabricated directly on a semiconductor material with the subpicosecond carrier lifetime. PC devices based on ion-implanted InP [57, 58], ion-implanted Si-on-sapphire [59, 60] amorphous Si and low-temperature (LT) grown GaAs [60]–[63] have been studied thoroughly in recent years. All these materials are non-perfect semiconductors with artificially created deep-level traps to achieve their ultrashort carrier lifetimes. Unfortunately, ion-implanted semiconductors and amorphous Si also exhibit very low mobilities, which results in the low detectivity and low generation efficiency of such switches, as well as their poor long-term stability. The PC devices based on LT-GaAs films, grown by molecular beam epitaxy (MBE) in the 200°C to 350°C range on semi-insulating GaAs substrates are most often used in practical applications. The LT-GaAs material has been intensively investigated in the last decade, due to its subpicosecond carrier lifetime (≈170 fs), high resistivity (>10^12 Ω cm), high breakdown electric field (>300 kV/cm), and relatively large mobility (≈150 cm^2/Vs). All these properties are required for advanced, fast and sensitive, photodetectors and switches. The ultrafast photo-switches require nonstandard materials, fabrication, or operation, thus, they are very difficult to integrate in standard electronic or optoelectronic circuits based on high quality, monolithic Si or GaAs. Hybrid integration using special multi-chip modules or wire bonds have been commonly used, but such methods unavoidably reduce the intrinsic multi-gigahertz bandwidth of the devices. The integration problem even exists for LT-GaAs, since it is very difficult to grow the LT-GaAs layer at a desired position on already processed GaAs wafer, not to mention the impossibility to grow such layer directly on a Si substrate, which is the most widely used material in electronics.

In this work will be presented several possibilities for a host substrates. Materials with high temperature conductivity as a Silicon were chosen. We need to increase the input power of photomixer devices [74, 75] and materials with high breakdown voltage [76] (Sapphire, MgO, polyethylene terephthalate) are needed. Principle of Lift-off technique, which was used for the fabrication of freestanding photoconductive switches and photodetectors as describes Chapter 3. Figure 3.10 shows SEM photograph of LT-GaAs switch, which was replaced to predefined well on Silicon and contacted with CPS. The electrical transients generated by our devices were recorded with the help of an electro-optic (EO) sampling system featuring ≈200 fs time resolution. Figure 5.28 shows the transient photoresponse signals of this switch. The signal exhibit less than 0.5 ps FWHM, but after major signal there are also recorded next peaks, which come from the silicon substrate. LT-GaAs layer with the thickness 1 μm which was replaced on silicon substrate is not good isolated from the substrate at higher biases. For our next experiments with silicon there was evaporated 2 μm thick SiO₂
Figure 5.28: Transient photoresponse signal of LT GaAs photoswitch based on Silicon substrate. Measured at 100 V bias with input power 3 mW. Figure 3.9 in Chapter 3 shows photograph of this switch.

Figure 5.29: Transient photoresponse signals of LT GaAs photoswitch based on SiO$_2$/Si substrate. Structure was illuminated at 810 nm with input power 3 mW.

layer on Silicon substrate, which can good isolated LT GaAs layer from silicon, because in this material photogenerated carriers with a long carrier lifetime creates. Figure 5.29 shows an improvement of the transient photoresponse signals from this photoswitch with SiO$_2$ layer between substrate and active LT GaAs layer. In figure 5.30 is presented typical microswitch with CPS lines on host substrate. Figure 5.31
shows typical current-voltage characteristics of freestanding LT-GaAs transferred on top of a sapphire substrate, plastic and Si/SiO$_2$ substrates, as well as, for 'as-grown' LT-GaAs on native GaAs substrate, measured in the dark condition. The 'as-grown' samples exhibit ohmic dependence up to $\sim$10 V and at higher bias nonlinear behavior is observed. On the other hand, the freestanding devices show ohmic behavior in the whole range of applied voltages up to 200 V (corresponding to average electric field of 200 kV/cm). Furthermore, the figure 5.31 demonstrates that freestanding structures exhibit more than 10-fold decrease of the dark current as compared to the 'as-grown' devices, and they show no sign of electrical breakdown up to 200 V of dc bias. We ascribe this improved performance to the substantially higher bandgap energy of sapphire and SiO$_2$ ($E_{gap}^{GaAs} = 9.0$ eV, $E_{gap}^{SiO_2} \approx 8.0$ eV) as compared to the native GaAs substrate ($E_{gap}^{GaAs} = 1.42$ eV). The substrates, though, have relatively poor thermal conductivity at room temperature ($\alpha^{GaAs} \approx 0.35$ Wcm$^{-1}$K$^{-1}$, $\alpha^{SiO_2} \approx 0.14$ Wcm$^{-1}$K$^{-1}$, and $\alpha^{Si} \approx 0.59$ Wcm$^{-1}$K$^{-1}$). Thus, the further improvement in room-temperature performance of our freestanding LT-GaAs devices (e.g. higher device biasing and increased optical illumination power) can be achieved by the film transfer on top of a substrates with high $\alpha$. On the other hand, sapphire exhibits extremely high $\alpha$ at low temperatures ($\alpha^{GaAs} \sim 100$ Wcm$^{-1}$K$^{-1}$ at 20 K) and is an ideal choice for cryogenic devices. LT-GaAs coupling with Si substrates is attractive as well, since it offers combination of good thermal conductivity of Si ($\alpha^{Si} \approx 1.60$ Wcm$^{-1}$K$^{-1}$) and large range of integration options with existing electronic devices. The electrical transients were measured at various bias voltages up to 120 V and excitation powers up to 3 mW. Nearly identical transients were recorded for different bias voltage. Two examples, for 18 and 111 V bias, are shown in figure 5.29. All records show the same FWHM of $\sim 0.55$ ps. More
important observation is that the response time (1/e decay time) does not depend on the applied bias up to 120 V and is \( \sim 0.37 \text{ ps} \) [77] (figure 5.32, right scale). This is in contradiction to generally well known fact that the response time in LT GaAs increases strongly with applied bias voltage (e.g. \( \sim 0.3 \text{ ps} \) at \(<10 \text{ V} \) and \( \sim 5 \text{ ps} \) at \( \sim 50 \text{ V} \) [12]). This effect was attributed to thermal effects [78] or to a reduction of the electron capture cross section with increased electric field as reported recently [12]. However, another explanation might be that the high field region, which is located near the contacts, penetrates partially into the GaAs substrate at high biases and thus some 'slow' carriers can be excited. Note that the sheet resistivities of annealed LT GaAs layer and semi-insulating GaAs substrate are comparable. Nevertheless, our result underlines the advantage of presented 'LT GaAs on Si' structures to achieve short response times at high voltages. The response amplitude as a function of applied bias, measured at the excitation power of \( \sim 0.46 \text{ mW} \), is shown in figure 5.32 (left scale). At low biases the pulse amplitudes increase linearly with voltage, as expected. At higher biases the amplitude saturates, which indicates that the collection efficiency decreases. Similar dependences were observed also for another excitation powers and the saturated amplitudes exceeded 1 V at higher powers.

Figure 5.33 shows the frequency response of the 'LT GaAs on Si' microswitch obtained from the uncorrected transient measurements using fast Fourier transform (FFT). The FFT results for 27, 55 and 119 V bias voltage are shown as examples. The -3dB bandwidth for all bias voltages up to 119 V is about 500 GHz. This is nearly the same bandwidth as obtained for LT GaAs on GaAs substrate [16]. Some peaks observed in the frequency responses above \( \sim 200 \text{ GHz} \) may be due to non-optimized CPS strips.

Also on the SiO\textsubscript{2}/Si substrate were observed for higher input powers thermal heating effects indicated by decreasing of responsivity (see figure 5.34) and these results are in agreement with photoresponse amplitudes of the photoresponse transients as a function of the input power in figure 5.35. The photoresponse amplitudes saturate with increasing of input power and this could be explain due to the overheating effects. This plays big role on the substrates with pure thermal conductivity. One of these materials are polyethylene terephthalate which has relative low thermal conductivity but there is an increasing interest in the development of semiconductor electronic devices and circuits on flexible plastic substrates. Encouraging results have been obtained at the preparation of field-effect transistors [79] light emitting diodes [80] and displays [81], as well as thin-film solar cells [82]. Moreover, electronic devices like magnetic storage disks [83] and pyroelectric sensors [84] on flexible substrates are also under investigations. However, there is a lack of knowledge on fast photoelectric switches and photodetectors on plastic substrate. Such devices might have large potential in various applications ranging from low-cost contactless switching to high performance aircraft applications. Polyethylene terephthalate (PET) is mostly used as a plastic substrate [79]-[84] due to its very good mechanical (flexibility), electrical (surface resistivity \( \sim 10^{13} \Omega \text{ sq} \), optical (light transparent) and chemical (acid resistance) properties [85]. However, the PET substrate cannot heated above \( \sim 125 \text{ °C} \), therefore a 'low-temperature' preparation procedure needs to be used. The current–voltage \( (I-V) \) characteristics (figure 5.31) in the dark and under 850 nm continues-wave illumination of prepared LT GaAs
photodetectors were measured at first. They exhibit ohmic behavior in wide range of biases (≤60-70 V). Space-charge effects were not observed, which indicates on efficient suppression of high-field region near the contacts.

The devices exhibit low dark currents, about $6 \times 10^{-9}$ A at 10 V and $≤10^{-7}$ A at 100 V, and breakdown voltages of 110-130 V, which are similar to those we observed on freestanding LT GaAs microswitches [76]. From EO measurements obtained waveform
exhibits an 0.7 ps full-width-at-half-maximum (FWHM) time and an 0.6 ps response time obtained from the amplitude drop to its 1/e value. These are fully comparable values to those reported on non-separated LT GaAs (i.e. on native GaAs substrate) [10] as well as on freestanding LT GaAs [76]. It should be noted that some resonances are observed in the waveforms, probably connected with non-optimal geometry of used CPS lines.

![Figure 5.36](image1.png)  
**Figure 5.36:** Response time and amplitude of electrical transients of the LT GaAs/PET photodetector as a function of applied bias voltage for 2 and 10 mW optical power. The dotted lines are only for eye.

![Figure 5.37](image2.png)  
**Figure 5.37:** Response time and amplitude of electrical transients of the LT GaAs/PET photodetector as a function of optical input power for 30 V and 97 V bias voltage.

Detailed analysis of recorded electrical transients of LT GaAs/PET photodetector under various applied bias voltages up to 100 V and optical powers up to 10 mW was performed. Device response time and amplitude as a function of applied bias voltage are shown in figure 5.36. Response times down to 0.55 ps and amplitudes up to 1 V can be achieved. However, different device behavior follows from evaluated data for lower and higher biases with a cross-point at 70–75 V. In the "lower-bias" region the response time is constant and the amplitude increases proportional with the bias, as one would expect. On the other hand, the response time increases and the amplitude saturates if the bias voltage is increased above 70–75 V. This indicates on the influence of heating effects at higher biases. One should consider that the thermal conductivity of PET substrate is relatively low (0.15 W m⁻¹ K⁻¹) and the optical power density, even if pulsed, is 2.5 kW/cm² for our 20×20 μm² device. Stronger increase of the response time for 10 mW optical power in comparison with that for 2 mW supports this assumption. However, an increase of the response time of LT GaAs photoswitch with increased bias voltage has been reported previously [12]. The authors attributed this effect to a reduction of the electron capture cross section with increased electric field. In contradiction to this, we reported recently on constant response time (0.37 ps for biases up to 120 V) for LT GaAs photoswitch with similar geometry as used here and
transferred on highly thermally conductive SiO$_2$/Si substrate [77]. The response time and amplitude of LT GaAs/PET photodetector evaluated from recorded waveforms measured at constant bias voltage and increased optical input power up to 10 mW are shown in figure 5.37. Data for two selected bias voltages, 50 and 97 V, as examples of low- and high-bias behavior, are only shown. For 50 V bias voltage the response time is nearly constant, increases slowly from $\sim$ 0.6 to 0.8 ps, with increased excitation power. This confirms above described result that heating effects does not play a significant role at biases below 70-75 V. For 97 V bias voltage an increase of the response time with the input power is stronger and 1.7 ps response time is evaluated for 10 mW input power and 97 V bias. From this it follows that, depending on the bias and input power conditions, LT GaAs/PET photodetector performance with subpicosecond response time and amplitudes up to $\sim$ 0.7 V or 1–2 ps response time and amplitude as high as 1 V can be obtained.

### 5.4 MSM geometry optimization

Output power of the photodetectors and also photomixers is directly connected with bias voltage applied to device. The bias voltage should be high as possible because of $P_{\text{out}} \sim V_b^2$. The figure 5.38 shows the breakdown voltage for devices with different finger contact geometry. Similar tendency as for reduction of the capacitance with increased $s + w$ and $s/w$ is found. However, a compromise needs to be considered to achieve a

![Figure 5.38: Electric field distribution, i.e. breakdown voltage, depends on the finger contact geometry. Highest breakdown voltage is found for structures with finger width $w = 0.7 \mu m$ and finger spacing $s = 2.8 \mu m$.](image1)

![Figure 5.39: Responsivity of MSM structures for various finger spacing / width. Measured at bias voltage 20 V and 40 V. Structures were illuminated with input power 190 \mu W.](image2)
reasonable transit time with respect to the carrier lifetime and following decrease of the
responsivity for higher \( s + w \) and \( s/w \) \[87\]. Figure 5.39 shows results from responsivity
characteristics of MSM structures with various finger contact geometry. It was observed
that responsivity is higher for smaller finger-spacing-to-width ratio \( s/w \), as well as, for
lower \( s + w \) values. This fact is in contradiction to requirements for the capacitance
and breakdown voltage as a function of the finger contact geometry. For optimal
 electrical properties of MSM photodetectors an compromise between sensitivity which
 is function of responsivity and the "speed" of photodetector should be done where the
 response time of photodetector is function of capacitance when carrier lifetime is in
 femtosecond range. Large sensitive area detectors are required for plastic optical fiber
 based communication that finds an increasing importance in recent years \[88\]. An
advantage solution for large area photodetectors should be special geometry of MSM
structure also called "TWINS".

A modified design of interdigitated MSM structure is presented in the figure 5.40.
This design reduces a device capacitance and improves the ratio of dc-photoreponsivity
to device capacitance over a standard MSM design about a factor of 2 that is particu-
larly important when applied to a large area photodetector. Recently, electrically
stacked MSM structures were used to reduce input capacitance of optoelectronic inte-
grated receiver \[89\].

![Figure 5.40: Principal comparison between standard and TWINS geometry of the MSM
structure. Dividing an original area of MSM structure onto two separate ones connected
in series leads to the reduction of capacitance of the system.](image)

Dividing an original area of MSM structure onto two separate ones connected in
series leads to the reduction of capacitance of the whole system to one fourth of origin-
al one, while keeping active area of each MSM of one half (see inset in the figure
5.40). In that way, it is expected that the photodetector's figure-of-merit in the term
of the dc photoresponsivity per unit device capacitance should increase by a factor of
two for modified (hereafter called Twins) structure. Modified MSM design was verified
on photodetectors made of low-temperature-grown gallium arsenate. Such material as
was presented earlier in this work (see Chapter 2) and it's well known with picosec-
ond and subpicosecond lifetime of the photogenerated charge carriers that guarantees
capacitance-limited time response of the MSM structures. Interdigitated finger elec-
trodes with finger spacing of 2 μm and finder width of 1 μm were formed by electron-
beam-lithography and lift-off technique. Devices had an area from about 100×100 μm²
down to 10×10 μm² and were connected to the feeding coplanar strip lines with the
characteristic impedance of 90 Ohms. A standard pump-probe time resolved experi-
ment (see Chapter 4) was performed to access temporal response of fabricated MSM
structures. Theoretical values of response time are presented in the figure 5.41. These
values show that the effect of decreasing response time for small area photodetectors
will be more clear for structures based on the materials with short carrier lifetime.
With increasing of carrier lifetime the effect of decreasing of response time will be
detected for larger area photodetectors.

It was tested both DC and high frequency performance of modified MSM structure.
Figure 5.42 makes a comparison of the DC responsivity of standard and modified
MSM structures. Finger width and spacing were 1 and 2 μm, respectively, while the
area of the MSM was 100000 μm². For a of 40 V and a light-input power of 140 μW,
the DC response of 65 mA/W and 33 mA/W were found for standard and modified
MSM, respectively. Responsivity does not exhibits tendency to saturate up to the
device breakdown voltage as is known (expected) for standard MSM and for LT GaAs
based device. However, such behavior is typical for a photodetector in which dc-
responsivity is limited by a short lifetime of collected photogenerated carriers, that is a
case expected for LT GaAs based MSM photodetectors used. Observed dc-responsivity
of TWINS structure is slightly higher than an one half of original (standard) structure
and depends on finger width/spacing configuration. However, no clear correlation was
found.

Figure 5.43 shows measured response time in the term of FWHM measured for both
standard and modified MSM structures with various areas. Observed response times
exhibited saturation at about 2.2 ps when an active area of tested devices decreased.
This value where found out the same regardless of structure type and it seems to be a
response time limited by the lifetime of photogenerated charge carriers in the LT GaAs
used.

The response of the large area MSM is slower than the four times faster response
predicted by theory due to a decrease in device capacity was not observed for TWINS
structures. This should be tentatively attributed to slower response and to a time
varying potential of the middle electrode owing a floating potential when a structure is
exposed to the illumination. However, further extensive experiments would shed more
light on this problem and help to explain actual phenomenon behind this observed
behavior.
Figure 5.41: Theoretical values of photodetector response time for different charge carrier lifetimes.

Figure 5.42: Measurement was done at room temperature with laser source connected to fiber having optical power of 140 µW at wavelength 855.6 nm.

Figure 5.43: FWHM of the temporal response of the MSM structures as a function of active area of device measured for standard and modified design of the MSM.
Chapter 6

Photomixers

Generation of terahertz radiation by photonic techniques like difference-frequency mixing in ultrafast low-temperature grown GaAs (LT GaAs) photodetectors has been studied extensively for the last decade [90]. Since the development of lasers, optical heterodyne conversion (photomixing) has been very useful for coherent detection in many regions of the electromagnetic spectrum. Photomixing was also proposed as a technique for generating coherent radiation in the microwave and the millimeter wave regions [1], and interest in this technique has been revived recently by the advances in high speed III-V device technology [91, 92]. From the two applications, coherent generation has been much less useful than coherent detection because of the lack of a suitable photomixer. Although difference frequencies have been generated up to 5 THz [16], the only drawback accounted in the state-of-the-art photomixers is very low conversion efficiency, one of the key parameters. The low output power is directly connected to low conversion efficiency. The generated power is severely limited by at least one of several factors such as: 

i/ low photomixer bandwidth; ii/ poor optical power coupling; iii/ impedance mismatch between the photomixer element and the load circuit; iv/ degradation of the photomixer properties at high optical pump power.

As it was presented by Brown and co-workers [93, 94], in their pioneering work on photomixing in LT GaAs up to 3.8 THz, the output power of photomixers with logarithmic spiral broadband antenna of 3 μW and 0.7 μW was obtained at frequencies of 460 and 850 GHz, respectively. Output power from photomixer devices with long dipole antenna [95], as well as in the traveling wave photomixer [96], reached values in the range of 10-100 nW at 0.5-2 THz. P. Chen et al. obtained rotational spectra of acetonitrile (CH₃CN) at 313 GHz with assistance of the photomixer device producing 400 nW at 300 GHz [97]. Photomixing experiments were also performed by Steen et al. reaching 60 nW at 440 GHz [98]. Terahertz generation between 200 GHz (about 1 μW) and 3 THz (about 1 nW) was presented by Peytavit et al. [99]. In their next measurements on the photomixers with vertical MSM structure, similar values with maximal 0.5 μW at 700 GHz [100] were reached.

Theoretical analysis predict that a superior photomixer having for example 0.2 μm wide electrodes and gaps would have a temperature limited conversion efficiency of 2% at a low difference frequency, 1.6% at 94 GHz, and 0.5% at 300 GHz [2]. Actually, for a 45 mW pump power, at room temperature the output power approaches a maximum
value of -9dB at a bias voltage of 30 V. This represents an optoelectric conversion efficiency of approximately 0.3% [101]. One way how to increase the output power is to increase incident optical power or operation bias voltage, but it was shown that devices exhibit thermal burn-out. The burn-out is not surprising under these operation conditions because thermal conductivity of GaAs decreases rapidly with increasing temperature (approximately as $T^{-3/4}$) [102] up to at least 500°C. The thermal conductivity of GaAs is about six times higher at 77 K (3.1 W cm$^{-1}$ K$^{-1}$) than at 290 K (0.46 W cm$^{-1}$ K$^{-1}$) [102], thus an attempt how to increase the total output power is to operate device at low temperature and to utilize more thermally conductive substrate such as silicon [103], because the output power of the photomixer is currently limited by its thermal damage threshold [97]. It was observed that the pumping a photomixer with maximum optical power of 90 mW at 77 K leads to measured output power of 0.2 μW at 2.5 THz, approximately twice the maximum output power of a photomixer operated near 300 K [17].

In this work a systematic study of the photomixer design and fabrication in order to optimize its output power at 460 GHz for single dipole antenna is presented. Part of the experiments was done also on the photomixers with broad banding spiral antenna and on the traveling wave photomixers. The LT GaAs photomixers are prepared on the materials with various grown temperature as well as using resonant cavity material structures and various finger contacts geometry. Their properties are investigated based on their DC characteristics in the dark and under illumination and results obtained from the photomixing experiments under various input power are shown. An improvement in the output power up to around 2 μW of microwave radiation (460 GHz) is demonstrated. Recent results on traveling wave photomixers show an output power of 1 μW at 850 GHz.

6.1 Material optimization

Influence of the growth temperature of LT GaAs on the photomixer properties is described at first. The 1.5 μm thick LT GaAs layers used for the preparation of photomixers were grown on semi-insulating GaAs at substrate temperature of 225, 250 and 300°C. The photomixers with a dipole antenna have an active area of 8×8 μm$^2$ and fiber width/spacing of 0.5/2 μm (microphotograph of such photomixer chip is shown in Fig. 6.6). Figures 6.1 and 6.2 show the total current and the microwave (460 GHz) output power as a function of bias voltage measured at an incident laser power of 80 mW ($\lambda_1$, $\lambda_2 \approx 780$ nm). It is clear that the best photomixer performance is obtained on samples with 300°C grown LT GaAs ($P_{\text{out}} \approx 0.8 \mu W$). This observation confirms our previous result of higher DC responsivity for LT GaAs grown at higher temperature (see Chapter 2.1.2). For samples grown at 300°C the DC responsivity of 18 mA/W at 18 V bias was found (Fig. 2.6) comparing to 13 mA/W which follows from the mixing experiments. This indicates low photosensitivity degradation at higher input powers.

Relation between the DC and microwave responsivities as well as the output power of a photomixer was studied in details. Figure 6.3 shows the DC responsivity as a func-
tion of applied bias for two photomixers. Expected $R_{th} \sim V$ and $\sim V^2$ dependencies are observed. Responsivities up to $\sim 0.1 A/W$ ($P_{in} 0.19 mW$), which are good values for LT GaAs, were measured at higher bias voltages. On the other hand, lower photocurrents as expected were obtained from the two-color mixing experiments at which the total input power was 30 mW. Detailed analysis of this question has shown that a nonlinearity between the responsivity (i.e. the DC photocurrent) and the input power exists. This is demonstrated in figure 6.4 (open marks) for the input power of 0.06–0.4 mW. Such nonlinear behavior is well known for conventional GaAs and InGaAs PDs and results from space-charge effects at the M/S interface. However, these effects can be suppressed by optimizing the LT GaAs properties [9], which is also demonstrated in figure 6.4 (full marks). According to the theory, the output power $P_{out}$ of a photomixer depends quadratically on the responsivity $R_{th}$ and optical input power $P_{in}$ (see figure 6.5). The $P_{out} \approx R_{th}^2$ dependence is obtained. This result confirms again the fact that the space-charge effects are highly suppressed in our samples. Or, the other hand, from this it follows that the responsivity can be used as a good measure to evaluate the quality of the photodetector part of a mixer.

In the next samples with and without Bragg mirror are compared. Figures 6.7 and 6.8 show the total current and the output power as a function of bias voltage. Sample without Bragg mirror shows about 2 times higher photocurrent in comparison with sample with Bragg mirror. This could be explain due to the 1.5 µm thick LT GaAs layer in comparison with 0.5 µm thin LT GaAs layer for sample with Bragg mirror. However, measured output power is nearly the same for both samples up to 7V bias and for higher biases sample with Bragg mirror shows approximately 50%
Figure 6.3: Responsivity of 5×8 μm² MSM photodetectors as a function of applied bias and photocurrent at 20 and 35 V resulting from the mixing experiment \( P_{in} = 30 \text{ mW} \).

Figure 6.4: Responsivity of photomixers with 5×8 μm² active area as a function of input power.

Figure 6.5: 460 GHz microwave power as a function of DC responsivity.

Figure 6.6: LT GaAs photomixer with 8×8 μm² interdigitated MSM structure and dipole antenna.

higher output power. This is due to the reduction of overheating effects which could increase the carrier lifetime at higher input powers. The incident power density here is 1.25 μW/μm², comparing to previously reported for the thermal damage threshold of
about 1 μW/μm². Both samples indicate the same characteristics at repeated measurements – it means the material properties didn’t change at these high incident power. Material with AlAs/GaAs Bragg mirror can reduced accumulation of the heat because the thermal conductivity of both these materials is higher than for LT GaAs. Rapid increase of the output power for photomixers based on the material system with Bragg mirror was observed after increasing the thickness of active LTGaAs layer. Because with increasing of the thickness of this layer there is possible to generate a higher number of electron-hole pairs and so to increase the photocurrent. This situation is very clearly to see from figures 6.9 and 6.10. The maximal output power for sample with 1 μm thick LTGaAs layer was about one order of magnitude higher in comparison to sample with 0.5 μm thin LT GaAs layer.

### 6.2 Contact geometry optimization

For optimal electrical and optical properties of a photodetector it is necessary to optimize the contact geometry with respect to high breakdown voltage and highest as possible responsivity, as was presented in the part 5.4 of this work. These parameters are also key issues for increasing input power of the photomixer devices. The influence of the contact geometry on the output power of photomixer device as well as its cut-off frequency was at first studied on the structures with logarithmic spiral antenna (see figure 6.11) designed for the frequency range 17 GHz to 3.7 THz. The
MSM structures with different contact geometry, i.e. with the finger width of 0.2 μm and finger spacing of 1, 1.4 and 2 μm, were integrated with this antenna. Figure 6.12 shows the detail of the MSM structure with finger width/spacing 0.2/1 μm. Calculated capacitance changed for these structures from 0.85 fF to 1.9 fF. Theoretical -3dB bandwidth calculated for these structures increases rapidly from 178.5 GHz up to 401 GHz with increasing the finger spacing. Measured data show that the bandwidth is in the calculated range. Figures 6.13, 6.14 and 6.15 show measured output power as a function of frequency for these mixers (unfortunately, non-stable laser power in the range 70-80 mW is responsible for a scattering of measured data). Extrapolated data for two photomixers, with 1 and 2 μm finger spacing, are presented in figure 6.16. Higher output power in whole frequency range between 100 GHz and 2 THz is obtained for photomixer with smaller finger spacing. This fact is in very good agreement with our previous observations presented in Chapter 5.4. Regardless to these results it should be mentioned that also photomixers with different finger spacing integrated with a single dipole antenna designed for 460 GHz were fabricated and measured data are comparable to those obtained on samples with broadbanding spiral antenna. Output powers up to 2 μW at 460 GHz were measured on the photomixers with optimized MSM contact metallization and with active area 8×8 μm² as presented here on photomixers with broadbanding spiral antenna.

Two novel types of the finger contact geometry were designed and preliminary tested on photomixers with integrated broadband spiral antenna. Both are based on circular geometry instead of conventional straight contacts. The first one is an Archimedean spiral geometry (see figure 6.17). Our first observations show an increase of the break-
down voltage of this type of structure in comparison to the standard MSM structure, as well as an increase of the responsivity. These facts could be explained by homogeneous electric field present in the large part of the area between the contacts. It is also assumed that this contact configuration acts not only to collect photogenerated carriers but also as a broadband antenna for THz frequency range. The major reason for this is a "μm" size of the structure. Photomixing measurements in the frequency range from 100 GHz to 1 THz are presented in figure 6.18. Measured are photomixers fabri-
Figure 6.15: Output power as a function of frequency measured for input power 70-80 mW at 19 V bias. Photomixer is fabricated on the 0.5 μm thin LT GaAs layer with Bragg mirror. LT GaAs grown at 300°C. Finger width/spacing of MSM structure is 0.2/1.4 μm.

Figure 6.16: Extrapolated data of output power as a function of frequency for photomixers with different MSM contact geometry. Photomixer is fabricated on the 0.5 μm thin LT GaAs layer with Bragg mirror. LT GaAs grown at 300°C.

Figure 6.17: Detail of the novel archimedean spiral MSM geometry integrated with logarithmic dipole antenna. Finger width / spacing 0.2/1.8 μm.

Figure 6.18: Comparison of measured data for output power as a function of frequency for photomixers with standard MSM geometry and novel spiral MSM geometry. Structures were measured at 15 V bias and with input power 75 mW.

cated on the 0.5 μm thin LT GaAs layer with Bragg mirror, grown at 300°C, the bias voltage is 15 V and the input power is 75 mW. From these results an improvement of
the output power for this type of novel structure is clear in comparison to the standard structure. Next, an enhancement of the output power from a photomixer device with circular asymmetric contact geometry is demonstrated. The contacts configuration is shown in figure 6.19. This type of structure exhibits under illumination approximately the same currents in both bias polarities, as shown in figure 6.20. In comparison with standard MSM structure mixers with this novel circular asymmetric geometry exhibit ~80% higher output power at 400 GHz (see figures 6.21 and 6.22). Output power of ∼0.9 µW is measured at 20 V bias voltage and 60 mW input power. However, for this novel geometry a saturation of the output power at higher biases is observed in contradiction to standard contact configuration. Further investigations to explain this effect which initialized changes of the electrical properties are needed and they will be studied in the future.

![Figure 6.19: Detail of the novel asymmetric circular MSM geometry integrated with broadband spiral antenna. Finger width / spacing 0.5/1.8 µm.](image)

![Figure 6.20: Current-voltage characteristics under illumination with input power 16 mW measured on the photomixers with 1.8 µm thick LT GaAs layer. Growth temperature of LT GaAs layer is 250°C.](image)

Finally, advantages of recessed finger contacts presented already in chapter 5.2 (higher breakdown voltage, higher DC responsivity and shorter transient photoresponse signals) were proved directly on photomixer devices with integrated broadband spiral antenna. The preparation procedure of recessed contacts was described in chapter 3.2 and figures 6.23 and 6.24 demonstrate these devices in detail. Results of photomixing measurements at 200 GHz (80 mW input power) are shown in figures 6.25 and 6.26. Recessed structure exhibits higher current in the whole range of the bias voltages. This result is in full agreement with our previous observations. On the other hand, the output power at 200 GHz (figure 6.26) is improved only at lower bias voltages and a saturation occurs above 10 V bias. Frequency dependent measurements in the range from 0.1 to 1 THz on photomixers with 300 nm recessed contacts (see figure 6.24) and biased up to 10 V exhibit approximately two times higher output powers, as presented
Figure 6.21: 460 GHz output power as a function of bias voltage measured on the photomixers with active area 8×8 μm² with finger width/spacing 0.5/2 μm. Structures were illuminated at 780 nm wavelength with input power 16, 40 and 60 mW.

Figure 6.22: 460 GHz output power as a function of bias voltage measured on the photomixers with asymmetric MSM structure with active area 8×8 μm² and with finger width/spacing 0.5/1.8 μm. Structures were illuminated at 780 nm wavelength with input power 16, 40 and 60 mW.

Figure 6.23: LT GaAs photomixer with recessed logarithmic spiral antenna designed for frequencies up to 3.7 THz and also with recessed MSM contacts fabricated on the material with Bragg mirror.

Figure 6.24: Detail of the 8×8 μm² 300 nm recessed interdigitated MSM structure integrated with logarithmic spiral antenna.

in figures 6.27 and 6.28.

Another significant improvement of the photomixer performance is based on the result related to the contact metallization type (ohmic vs. Schottky), described before in chapter 5.1. More than three-times higher DC responsivities were found on structures using ohmic MSM contacts instead of conventional Schottky-type contacts (see figure
6.2. CONTACT GEOMETRY OPTIMIZATION

Figure 6.25: Current-voltage characteristics under illumination with input power 80 mW measured on the photomizers with recessed and surface MSM contacts. Fabricated on the 0.5 μm thick LT GaAs layer with Bragg mirror. Growth temperature of LT GaAs layers is 250°C.

Figure 6.26: 300 GHz output power as a function of bias voltage measured on the photomizers with broadening spiral antenna with active area of recessed and surface MSM 8 × 8 μm² with finger width/spacing 0.5/2 μm. Structures were illuminated at 780 nm wavelength with input power 80 mW.

Figure 6.27: Output power as a function of frequency at different bias voltage measured on the photomizer with surface MSM structure fabricated on the material with Bragg mirror and with the 0.5 μm thick LT GaAs layer (Tₜ = 250°C).

Figure 6.28: Output power as a function of frequency at different bias voltage measured on the photomizer with recessed MSM structure fabricated on the material with Bragg mirror and with the 0.5 μm thick LT GaAs layer (Tₜ = 250°C).
5.5). Higher photocurrents and output powers of photomixers, as shown in figures 6.29 and 6.30, were obtained recently by using this new procedure, up to now not reported in the literature. Photomixers with an ohmic contact metallization exhibit more than 3 times higher output power in comparison with the same structures but with Schottky contacts. An output power of 2.2 $\mu$W is measured at 460 GHz and applying an input power of 80 nW. Here it should be mentioned that the first photomixers prepared in the frame of this work have shown an output power at 460 GHz of 1–5 nW (2001, samples 13181). Further improvements in the device structure (DBR mirror, contact geometry etc.) have shown an increased output power up to 50 nW (begin of 2002) and later to 300–400 nW (end of 2002, samples 16025). This tendency has continued and 2.2 $\mu$W output power has been measured recently (figure 6.30). This is the highest value obtained in the frame of this work and fully comparable with those published in the literature for conventional structures [93]–[100]. A combination of ohmic metallization with novel spiral contact geometry and/or recessed contacts should further enhance the output power of a photomixer.

![Figure 6.29: Current-voltage characteristics under illumination with input power 75–80 mW measured on the photomixers with ohmic and Schottky MSM contacts. Fabricated on the 1.5 $\mu$m thick LT GaAs layer with growth temperature 300 °C. Between GaAs substrate and LT GaAs layer is 300 nm thin AlAs interlayer.](image1)

![Figure 6.30: 460 GHz output power at 75–80 mW as a function of bias voltage measured on the photomixers with single dipole antenna. In the graphic are compared photomixers with ohmic and Schottky MSM contacts. Finger width / spacing was 0.2/1.4 $\mu$m and MSM active area 8×8 $\mu$m².](image2)

### 6.3 Photomixers on host substrates

Further improvement of the photomixer performance can be obtained if negative influence of the GaAs substrate (generation of 'slow' carriers, low thermal conductivity,
etc.) can be eliminated, as already described in chapter 5.3. Lift-off technique of LT GaAs (see chapter 3.4) was successfully used for fabrication of the first hybrid optoelectronic circuits based on the micrometer size LT GaAs layers integrated with various substrates (Si, sapphire, MgO) [75]–[77]. Flexible and transparent substrates open new possibilities to many new applications in the scientific research.

Figure 6.31 shows the photomixer device with replaced $20 \times 20 \mu m^2$ LT GaAs layer
with the thickness of about 1 \( \mu \text{m} \) on the silicon substrate. We used silicon substrate because of its three-times higher thermal conductivity in comparison with native GaAs substrate. The surface of Si substrate was covered with 1 \( \mu \text{m} \) thin SiO\(_2\) layer to achieve good electrical isolation between the LT GaAs and Si. Perfect contact between SiO\(_2\)/Si surface and LT GaAs layer is necessary for reducing of accumulated heat. However, it is very difficult to adjust lifted-off LT GaAs of micrometer size into the pre-positioned etched groove on silicon substrate, as shown in figure 6.32. Thus, used procedure needs to be improved. One preliminary result of a mixer on Si substrate is shown in figure 6.33. An improvement of the output power is clear. Unfortunately, fabricated structure was burned-out at low biases which correspond to only 12 kV/cm average electric field. This is probably due to not fully optimized mechanical contact between replaced LT GaAs layer and host substrate. Nevertheless, more than 9-times higher output power at 460 GHz and low biases has been obtained (figure 6.33).

Another type of a photomixer on a host substrate has been recently designed and first devices prepared. They consist of vertical MSM detector integrated with single dipole antenna on MgO substrate, presented in figure 6.34. With assistance of lift-off technique a 1.5 \( \mu \text{m} \) thick LT GaAs layer with top contact was replaced into the pre-positioned 1 \( \mu \text{m} \) deep groove in MgO substrate. Bottom contact, which consists of Ti/AuGe/Ti metal layer system, was created in the etched groove before. This bottom contact serves not only as an electrical contact but we suppose that this metallic layer will decrease heat accumulation in the active area of the MSM structure and so the output power of the photomixers will be increased. Whole structure was connected to the single dipole antenna with Ti/Au metallization. From the DC measurements (see

![Figure 6.34: Detail of the vertical LT GaAs MSM structure based on the MgO substrate with metallic bottom and top contacts integrated with single dipole antenna.](image1)

![Figure 6.35: Current-voltage characteristics of vertical LT GaAs MSM structure at the dark and under illumination with input power 150 \( \mu \text{W} \) measured on the 1.5 \( \mu \text{m} \) thick LT GaAs layer growth at temperature 250 \(^\circ\text{C}\).](image2)
6.4 Traveling Wave Mixers

The traveling wave ("TW") concept [96] has several advantages in comparison to conventional photomixers reported in this work before. The main difference to a MSM-mixer is that the mixing process occurs distributed along a waveguide. The major advantage is that this type of device circumvents RC constant limitation. Therefore the interference of the two near-IR (here: 780 nm) diode laser foci has to occur in the form of interference fringes running at the speed of the THz-wave on the waveguide, in order to obtain phase-matching. This defines an angle between the two wave-fronts of the laser foci length, which is proportional to the difference frequency of the lasers. Because of these perspectives, TW-based photomixers were also prepared utilizing preparation procedure developed for conventional devices.

![Bow-tie antenna](image1)

![Recessed MSM structures](image2)

**Figure 6.36:** LT GaAs traveling wave photomixer with a finger width/spacing 0.5/1.4 μm interdigitated MSM structure and bow-tie antenna.

**Figure 6.37:** Detail of the recessed interdigitated MSM structures integrated in CPS-Part of the traveling wave photomixer.

Figure 6.36 shows the photograph of traveling-wave-MSM-waveguide with bow-tie antenna. In this case larger mixing area (e.g. 4 μm x 200 μm) allows to increase the input power up to 350 mW, what is possible due to an increase of cooling efficiency and so eliminated overheating effects. Such improvement permits the proportional increase of output power from the photomixer device. From our previous observations (see chapter 6.2) is clear that optimization of the MSM geometry contributes to an increase of the efficiency of collection of photogenerated carriers. From this reason...
MSM structure was integrated between coplanar strip lines. We fabricated a set of samples with different finger spacing. Best results were obtained on MSM structures with a finger width/spacing of 0.5/1.4 μm, what is in very good agreement with our previous observations. Next improvements are possible with recessing of MSM contacts as it is presented in figure 6.37. Figure 6.38 shows the output power of the TW photomixer in the frequency range from 850 GHz up to 1.6 THz and using an input
power of 280 mW. The output power decreases approximately with a slope $1/f^2$, which indicates on only one time constant to be involved (i.e., on absence of $RC$ constant). The output power at 850 GHz as a function of applied bias at input powers of 153 and 345 mW is shown in figure 6.39. The output power of the photomixer increases quadratically with increased bias, as expected. Here it should be noted that this photomixer was fabricated on material structure without AlAs interlayer, because of controversial results on structures with and without AlAs interlayer reported before (see figures 2.10 and 2.11 in Chapter 2). On the other hand, measured data does not show any saturation of an input power also at higher input powers. Figure 6.40 shows the output power characteristic as a function of input power. The major reason for this effect is, of course, distribution of the input power on the large area, which decreases accumulation of heat in the active area of the photomixer. The maximum output power of 1 μW at the input power of 345 mW and bias voltage of 20 V corresponds to the conversion efficiency of $\sim 3 \times 10^{-4}$% at 850 GHz. This is higher conversion efficiency than Matsuiura reported before on TW mixers [96] and comparable value to the best data on conventional MSM photomixers [93], as it is shown in figure 6.41. Further advantage of this MSM-TW photomixer is lower decrease of the output power with increased frequency ($P_{\text{out}} \sim f^{-2}$ instead of $\sim f^{-4}$ in conventional photomixers), i.e., higher conversion efficiency in the frequency range above 1 THz.

Figure 6.41: Conversion efficiency as a function of frequency for MSM-TW photomixer (dots are measured data at 20 V bias, stars are expected values for 25 V bias) in comparison with data published on MSM and TW photomixers (open marks).
Chapter 7

Conclusion

The aim of this work was to design and prepare photomixer devices based on LT GaAs and to optimize them with respect to the maximal output power. Essential part of the photomixer is the MSM photodetector structure. For this reason a major part of the optimization process was done on photodetector structures. One set of our photomixers was optimized for the 460 GHz output frequency employing single dipole antenna. The second set of photomixers used broadband bow-tie and spiral antennas designed for the frequency range up to 1.6 THz and 3.7 THz, respectively.

The influence of the growth temperature of GaAs on its desired properties (high resistivity, high electric breakdown field, low carrier lifetime, etc.) is presented in Chapter 2. It is well known that with increasing the growth temperature the carrier lifetime in this material increases as well. This is a major parameter for limitation of the maximal output frequency of a photomixer device, that is not RC-constant limited. The second important factor for optimization of the maximal photomixer output power is the mobility of photogenerated carriers. It is a well established fact that with increasing the growth temperature the mobility also increases in GaAs material. The output power of a photomixer device depends on both above mentioned parameters which are in trade-off. Thus, the growth temperature is one of the most important parameters contributing to the output power increase of our photomixers. Photomixers designed for 460 GHz require partially higher growth temperature of LT GaAs, 275–300 °C, as shown in Chapter 6.

Ion implantation is another possibility how to decrease carrier lifetime in GaAs. In this work we present results showing that employing this technique fabrication of materials with subpicosecond carrier lifetime is possible. Materials implanted with various ion doses ($10^{12} - 10^{16}$ ions/cm$^2$) and implantation energies in the range 82 keV–880 keV were prepared and their properties and dynamics before and after annealing were studied. Photodetectors based on 880 keV nitrogen-implanted GaAs show 50% higher sensitivity than our best LT GaAs photodetectors. These results outline new possibilities for increasing of photomixer output power because with right choice of implantation energy and dose it is possible to prepare materials with subpicosecond carrier lifetime and with higher mobility of photogenerated carriers than in previously reported materials. It was also shown that photodetectors based on the nitrogen-implanted material has improved electrical properties only for implantation energy
exceeding 700 keV. We ascribe these results to the fact that the concentration profile for lower implantation energy allows collection of slow carriers from non-implanted GaAs region. For our future work it is necessary to increase implantation energy to eliminated these effects. We believe also that with the optimal concentration of incorporated nitrogen ions in GaAs will initialize not only band gap reduction in this material but as was observed also at the doses 10^{19} ions/cm^2 material will indicate subpicosecond carrier lifetime. With increasing the implantation dose we believe that the material can be used for photomixers and detectors with subpicosecond carrier lifetime also for wavelength in infrared spectrum range, as illustrated Chapter 2. Next, very important observation is that nitrogen implanted GaAs material can be used, due to its radiation hardness, as the material for detectors in nuclear technique exhibiting subpicosecond carrier lifetime for wavelengths down to 352 nm, with sensitivity comparable to 800 nm wavelength.

Our next results show that for increasing of the photomixer output power it is necessary to use Bragg mirror between active the LT GaAs layer and the GaAs substrate, with thickness of the LT GaAs layer being important parameter. Doping of LT GaAs layer with beryllium at concentration of 10^{19} cm^{-3} shows that these material have carrier lifetime near to the 100 fs and photodetectors based on this materials indicate more than 100% increase of photodetector sensitivity in comparison with the undoped LT GaAs based devices. On the other hand Be-doped material shows that the carrier lifetime depends on the electric field intensity, in comparison with undoped materials. This fact was observed on the micrometer size GaAs photodetector structures separated from the native GaAs substrate and integrated with the various host substrates and with coplanar transmission line structures. Sapphire, MgO and Si/SiO_2 substrates were chosen to eliminate the influence of photogenerated slow carriers from the substrate.

It was observed that carrier lifetime in the undoped LT GaAs replaced structures is constant for the voltage bias up to 100 V. For fabrication of these structures we used, for the first time an improved LT GaAs lift-off technique, enabling us to fabricate microscopic size photoconductive switches. Lift-off technique is well now for more than one decade. However, only in this work we for the first time placed LT GaAs structures with size down to the 10 × 20 μm² and with the thickness from 0.5 μm to 1.5 μm on the variety of host substrates. The major motivation for improvement of classical used lift-off technique was that native GaAs substrate has relatively low thermal conductivity (0.46 W/cmK) and placing the active LT GaAs layer on top of the substrate with higher thermal conductivity as a silicon (1.5 W/cmK) could increase the output power from the photomixer devices, due to elimination of heating effects. Our results, presented in the Chapter 6, confirm the latter expectations. With assistance of lift-off technique we prepared the novel vertical LT GaAs photomixer structure. An active LT GaAs layer was placed on metal layer creating bottom contact, which plays three important roles. First, there is created metallic contact, this in the same time is used as cooler of the structure and so is possible to decrease the accumulation of heat during illumination. It is, therefore possible to pump higher input power into structure and increase output power from photomixer. The last function of the bottom metal contact is that it works as mirror for input wavelengths and so it is possible to use the input power much more
effectively as in classical possibilities.

We also, for the first time, present in this work that LT GaAs based photodetector on flexible plastic substrate exhibits subpicosecond responses. This fact together with realized photolithography offers new era for fabrication of sources of subpicosecond electrical pulse, which are needed in many applications. Photonixer devices based on plastic substrate are in progress and so will possible decrease losses from absorption of the signal, because this material is transparent in THz range. Last advantage is the excellent mechanical properties of polyethylene terephthalate substrate which was used for fabrication of our first photodetector and photonixer devices, which are in this case much more robust. This novel type of plastic-based structures will be possible to use also in the genetic diagnostic test technique integrated with THz systems in DNA analyses, because of inexpensive and easy destruction of the test structures contaminated with various organic materials as virus, bacterial sources etc.

Everybody knows that in principle, it is possible to fabricate on a semiconductor two types of metallic contacts. Up to now, people in presented data use for LT GaAs usually Schottky type of MSM contacts, based on the simple evaporation of metallic layers on the LT GaAs surface. In this work were applied well know principles from GaAs technology for creation of ohmic contacts also on the LTGaAs. It is first time presented this way for improvements of electrical properties of photodetector and photonixer devices. Photodetectors with ohmic contacts exhibit under some conditions approximately 3 times higher sensitivity than devices with Schottky contacts, with no influence on the response dynamics of photodetector device. This is the most important improvement of technology of fabricated photonixers, because also output power from our photonixer devices with ohmic contacts exhibits approximately 3 times higher values than Schottky contact based devices. With this improvement our devices exhibits more than 2 pW output power at 460 GHz.

In this work were also studied influences of various MSM contact geometry on photodetector electrical properties with respect to RC constant limitation and responsivity of devices. It was observed that also with optimization of MSM geometry it is possible to increase the output power from photonixer up to 200% with decreasing of finger spacing from 2 μm down to 1 μm with respect to the total capacitance which could not be higher that will limited device with RC constant. First results from photonixers with asymmetric and spiral geometry of MSM photodetector structure are presented in Chapter 6. The major motivation for fabrication of novel asymmetric geometry is that with decreasing of the negative electrode will be possible to eliminated the hole current component (because holes are slower than electrons) and they contribute to the longer responses of photodetector device. This hypothesis was not observed in our measurements for both directions of applied bias photonixer devices show approximately same output power in the frequency range from 100 GHz to 1 THz. Next observations in the future are needed to explain the carrier dynamics in asymmetric MSM structures. Novel spiral MSM photodetectors structure show increasing of sensitivity in comparison with devices with classical MSM structure as well as higher breakdown voltage, because of reduction of geometry factor dependent on electric field. From photomixing measurements it is clear that the spiral geometry MSM structure is not limited by additional inductance of the structure and photonixer with this novel MSM structure
exhibits in the whole frequency range approximately 3 times higher output power than conventional device.

Photomixers with traveling wave concept also show at frequency 850 GHz about 1 μW output power at more than 300 mW input power. This concept has one advantage because input power is distributed on large photoconductive area and so are eliminated overheating effects.

Last improvement, necessary for photomixer devices, is that MSM contact could be also fabricated not only on the surface of photoconductive material, but also in the material. Recessed contacts exhibit higher breakdown voltage, which depends on the depth of recession. In this work we also observed that photodetectors with recessed contacts are more sensitive in comparison to MSM fabricated on the surface. Recessed contacts fabricated by wet etching and IBE are presented in Chapter 3. In both cases we observed sensitivities from 40% to 200% higher in dependence on the recession depth than for non-recessed structures. Very important fact is that recessed contacts could for optimal recession depth more efficiently collect photogenerated carriers from deeper regions and so not only increase total number of photogenerated carriers, but also in shorter time, because of decreasing of distance to the collecting electrodes. This was also observed in this work. Our first results from the photomixers with broadbanding antenna show in frequency range from 100 GHz to 1 THz approximately 2 times higher output power than photomixers with non-recessed contacts.

In the future combination of here presented improvements will be used to reach next improvement of electrical properties of photodetector and photomixer devices.
Kapitel 8

Zusammenfassung


Es konnte gezeigt werden, daß die Lebensdauer für undotiertes transferiertes LT GaAs konstant ist für Spannungen bis 100 V. Für die Herstellung dieser Strukturen wurde eine verbesserte Lift-off-Technik entwickelt, die es ermöglicht, mikrometergroße Strukturen zu transferieren. Die Lift-off-Technik ist grundsätzlich schon lange bekannt, allerdings konnten hier erstmals Strukturen bis 10×20 μm² herunter mit Dicken von 1.5 μm bis 500 μm auf verschiedene Substrate übertragen werden. Der Hauptgrund für die Verbesserung der klassischen Lift-off-Technik war die relativ geringe Wärmespeicherkapazität von GaAs-Substrat (0.26 W/cmK), verbunden mit der Aussicht, daß mit der Übertragung der aktiven LT GaAs-Schicht auf Substrate mit höherer Wärmespeicherkapazität, wie z. B. Silizium (1.5 W/cmK), die Ausgangsleistung der Fotomischer erhöht werden kann, da eine Aufheizung verhindert wird. Die erzielten Ergebnisse bestätigen diese Erwartungen. Mit Hilfe dieser Lift-off-Technik wurden vertikale LT GaAs-Fotomischer hergestellt. Die aktive LT GaAs-Schicht wurde auf eine Metallschicht übertragen, welche drei wichtige Aufgaben erfüllt: Zunächst dient sie als unterer Kontakt. Gleichzeitig verhindert sie das Erwärmen der Struktur während der Beleuchtung, wodurch es möglich ist, eine höhere Ausgangsleistung zu verwenden und somit die Ausgangsleistung zu erhöhen. Schließlich wirkt die untere Metallschicht als Spiegel für einfallende Wellen, so daß die eingestrahlte Leistung effektiver genutzt werden kann.

In dieser Arbeit werden auch erstmals LT GaAs-Fotodetektoren auf flexiblen Kunststoffsubstraten präsentiert. Dieses Material ist transparent im THZ-Bereich, wodurch Ver-
luste durch Absorption vermieden und die Ausgangsleistungen bei Fotomischern erhöht werden können. Die hervorragenden mechanischen Eigenschaften von Polyethylen-Terephthaltat (PET) als Substrat ist ein weiterer Vorteil. Diese neuartigen Plastik-basierenden Strukturen sind ebenfalls gut geeignet für Gentec's in Verbindung mit THz-Systemen in der DNA-Analyse, weil die mit organischen Material wie Viren, Bakterien etc. kontaminierten Teststrukturen kostengünstig und einfach zerstört werden können.


„Traveling-wave“-Fotomischer zeigen bei 850 GHz ebenfalls etwa 1 µW Ausgangs-
leistung bei 300 mW eingestrahlter Leistung. Dieses Konzept hat einen großen Vorteil, 
da die eingestrahlte Leistung auf eine große Fläche verteilt ist und somit Überhitzung 
vermieden werden kann.

Die letzte Verbesserung der Fotomischer war, daß die MSM-Kontakte nicht nur auf 
der Oberfläche des fotoleitenden Materials hergestellt, sondern in das Material versenkt 
 wurden. Die versenkten Strukturen weisen höhere Durchbruchspannungen auf, die von 
der Tiefe der Versenkung abhängen. Ebenso wurde beobachtet, daß Fotodetektoren 
mit versenkten Kontakten empfindlicher sind als auf der Oberfläche hergestellte. Ver-
 senkte Kontakte, hergestellt durch naßchemisches Ätzen bzw. IBE, sind in Kapitel 3 
beschrieben. In beiden Fällen konnten Erhöhungen der Sensitivitäten von 40–200%, 
abhängig von der Tiefe der Versenkung, gemessen werden. Der wichtige Effekt ist, 
dß bei versenkten Kontakten in optimaler Tiefe mehr fotogenerierte Ladungsträger 
aus tieferen Gebieten eingesammelt werden. Allerdings wird nicht nur die Gesamtanzahl 
der Ladungsträger vergrößert, sondern auch die Zeit verringert, da der Abstand 
der Elektroden effektiv verkleinert wird. Dies konnte in dieser Arbeit ebenfalls beob-
achtet werden. Erste Ergebnisse von Fotomischen mit Breitbandantennen zeigen im 
Frequenzbereich von 100 GHz bis 1 THz ungefähr doppelt so große Ausgangsleistung 
wie Fotomischer mit nicht-versenkten Kontakten.

Durch die Kombination von hier präsentierten Neuerungen können in Zukunft wei-
tere Verbesserungen der elektrischen Eigenschaften von Fotodetektoren und Fotomi-
 schern erwartet werden.
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