**A design of the structure of an integrated GaN photoreceiver for the UV range is presented. The circuit includes an MSM photodetector and an HFET based amplifier. Preliminary data for the design were obtained from the measurements performed on the test structures – CTLM, van der Pauw, Schottky contacts and also performed on discrete devices – MSM detectors, HFET transistors – all fabricated on AlGaN/GaN/sapphire substrates. Frequency response characteristics of the HFET based amplifier and also of the complete MSM-HFET photoreceiver were computer-simulated. One of the most important steps in device monolithic integration is isolation of the elements. In this project were considered two types of possible elements isolation: plasma etch (mesa) and implant isolation. A set of photolithography masks for chip fabrication on AlGaN/GaN layers was created. Anticipated fabrication of the designed MSM-HFET integrated photoreceiver in 1-µm geometry should allow its RF operation.**

**Keywords:** integrated photoreceiver, MSM, HFET, GaN.

1. **Introduction**

Optoelectronic integrated circuits (OEICs) have been intensively developed in recent years. A basic optoelectronic integrated detecting circuit contains a photodetector and an amplifier in its structure. Monolithic integration, in one chip, of the photodetector and an amplifying stage coupled with it allows obtaining a photoreceiver circuit with satisfying electrical parameters at a low unit price. Such photoreceivers, for IR spectrum using GaAs material system, have been designed and fabricated in the Semiconductor Device Laboratory at the Faculty of Microsystems Electronics and Photonics at the Wroc³aw TU. Also extensive studies are carried on the semiconductors for UV range. Investigations are focused on III-N material system, mostly on GaN and AlGaN semiconductors. The integrated UV photodetectors, based on such semiconductors, find many applications both in civil (ozone detectors, flame detectors) and military (jet engines monitoring, wireless short-distance communications) areas because they can work at high visible and infrared background radiation. Using aforementioned materials (GaN, AlGaN) involve difficulties in monolithic integration of the elements. One of them is a necessity of dry plasma etching for creating “mesa” type isolation of devices due to high robustness of the material. An alternative way for making isolation of elements can be an ion implantation.

The main objectives of this work were the following: to develop a structure of UV integrated photoreceiver in 1-µm geometry, to design an integrated MSM-HFET photoreceiver structure which can be also used as a discrete MSM (metal-semiconductor-metal) or HFET (heterojunction field effect transistor) device, and to allow the studies of two types of electrical isolation techniques in the fabricated circuits.

A design of the integrated photoreceiver structure was based on the preliminary data obtained from the measurements of electrical parameters of the test structures realised previously in our laboratory.

2. **Measurements of test AlGaN/GaN structures**

Several samples with discrete devices and the test structures were performed and measured. The structures were fabricated on Al$_{0.27}$Ga$_{0.73}$N(30nm)/GaN(2µm)/sapphire heterostructures grown by MOCVD at the Institute of Electronic Materials Technology (ITME) – Warsaw [1]. Metallisation of the ohmic contacts was made of Ti/Al/Ni/Au – 20/200/40/100 nm and alloyed at the temperature 850°C. The Schottky contacts were made of Ti/Pt/Au – 5/20/150 nm. The lift-off technique and e-beam evaporation were applied in both cases. Next, all metallisations were covered by Ti/Au – 15/200 nm layer to decrease their sheet resistance. The following structures were measured: CTLM (circular transmission line model), van der Pauwe’s, Schottky diodes with junction areas: 0.02 mm$^2$, 0.1 mm$^2$ and HFET transistors with channel width 0.33 mm and gate length 10 µm designed in circular configuration. Based on the obtained results, the following technological and device parameters were calculated: the specific resistance of ohmic contact $p_o = 1.12 \times 10^{-4}$ Ω cm$^2$, the AlGaN/GaN sheet resistance $R_{sh} = 500$ Ω (from CTLM
Design of a GaN UV integrated photoreceiver

structures [2]); the sheet resistance of ohmic contacts metallisation \( R_{\text{OHM}} = 0.32 \times 10^{-3} \ \Omega \), the sheet resistance of Schottky contacts metallisation \( R_{\text{SCHOTTKY}} = 3.15 \times 10^{-3} \ \Omega \) (from van der Pauwe structures); the Schottky barrier height \( \Phi_b = 0.89 \ \text{V} \) (from the Schottky diode structures); the transconductance \( g_m = 45 \ \text{mS/mm} \) and drain saturation current (at the gate-source voltage \( U_{GS} = 0 \ \text{V} \)) \( I_{DSS} = 170 \ \text{mA/mm} \).

3. Design of a photoreceiver structure

Electrical schematic diagram of the designed integrated photodetector is presented in Fig. 1. This circuit represents typical approach to construction of an integrated photoreceiver. The complete circuit consists of four elements: an MSM photodetector, a resistor and two HFET transistors. A detecting element is MSM photodiode biased by \( R_1 \) resistor. This resistor is also current to voltage converter which is changing the detector photocurrent into \( U_{GS-T2} \) voltage. This voltage is fed to the input of the amplifier realized by transistors \( T_1 \) and \( T_2 \). The transistor \( T_2 \) is a driver and \( T_1 \) is an active load. For correct establishment of the operating points of the active elements \( T_1, T_2 \), these transistors should have different channel width. A channel of the driving transistor \( T_2 \) should be about 10% narrower than the channel of the load transistor \( T_1 \). The circuit requires single supply voltage applied between \(+U_{dd}\) and \(-U_{ss}\) terminals. The photoreceiver’s output voltage signal appears at the “output” terminal.

Apart from the elements \( T_1, T_2, R_1, \) MSM, which form the circuit of the integrated photoreceiver, there are also the additional devices: MSM photodetector, Schottky diode and test patterns – CTLM structure and two van der Pauwe structures placed in the chip structure.

The preliminary assumptions for the chip design are the following:

1) chip dimensions of 900x900 \( \mu \text{m}^2 \) – resulted from the requirement of compatibility with other circuits, which are fabricated in the same wafer at the same time,
2) apart from the integrated photoreceiver circuit there are some discrete and test structures (CTLM, van der Pauwe) included,
3) HFETs and MSM photodetector are realized in 1-\( \mu \text{m} \) technology,
4) components of the photoreceiver are designed in such a way that performing measurements on each of them should be possible even in case of poor isolation parameters (leakage) – the transistors \( T_1, T_2, \) and the resistor \( R_1 \) are designed in circular configuration;
5) chip components are provided with appropriate contact pads to facilitate measurements by point probes or bonding, in case of using them as discrete elements – especially \( T_1, T_2, \) transistor’s structures are provided with appropriate contacts for a 150 \( \mu \text{m} \) pitch coplanar probe for on-wafer microwave measurements;
6) chip design allows for “mesa” (plasma etch) or implant isolation testing.

A topology of the transistors \( T_1 \) and \( T_2 \) was designed to obtain high transconductance – it means that their channels width should have the largest possible value, taking the given chip area into account. The rest of the chip area was shared by MSM photodetectors, van der Pauwe’s structures and Schottky diode. The designed topology of the chip is presented in Fig. 2. In Fig. 3, some details of MSM2 photodetector [Fig. 3(a)] and the transistor \( T_2 \) [Fig. 3(b)] are presented. The designed chip contains: two transistors – \( T_1, T_2 \) with the gate length \( L_G = 1 \ \mu \text{m} \) and the channel width \( W_{T1} = 706 \ \mu \text{m}, W_{T2} = 656 \ \mu \text{m} \), respectively, both in a circular configuration; two MSM photodetectors with the finger width \( w \) to the distance between the fingers \( s \) ratio as follows: MSM1 – \( w/s = 1/3 \ \mu \text{m} \), MSM2 – \( w/s = 1/2 \ \mu \text{m} \) (this photodetector is a component of the integrated photo-
The resistor \( R_1 \) of 90\( \Omega \) value – designed in circular configuration; test patterns – CTLM structure, two van der Pauwe’s structures and Schottky diode also in circular configuration.

The chip fabrication is possible with the usage of a designed set of eight photolithography masks. This set of masks allows making two types of elements isolation – mesa or implant, moreover it allows to make two types of chip surface passivation – by polyimide or Si\(_3\)N\(_4\) layer. The following masks are used for making: M1 – isolation (M1a – mesa isolation, M1b – implant isolation), M2 – ohmic contacts, M3 – subetching (optional), M4 – Schottky contacts, M5 – metallisation, M6 – chip passivation (M6a – polyimide, M6b – Si\(_3\)N\(_4\)), M7 – interconnections. Because of a specific property of implant isolation, a decreasing value of the surface sheet resistance, as a result of high temperature processing, all necessary high temperature process steps have to be performed before the ion implantation. It means that, in first order, the ohmic contacts must be made (deposited and alloyed). The usage of mask M3 is optional because the subetch process is not a main technological step in performing of the designed OEIC. In case of skipping M7 mask, the performed chip will not be an integrated circuit – it will be than a collection of discrete elements, which could be measured and applied in a hybrid circuit, for example.

4. Simulations

In order to estimate a frequency band of the designed photoreceiver computer simulations were performed in PSPICE program. The circuit shown in Fig. 1 was simulated. The MSM detector and both transistors were replaced with their small signal equivalent circuits shown in Fig. 4. The values of the elements of the equivalent circuits [MSM photodetector – Fig. 4(a), HEMT transistor – Fig. 4(b)] were calculated basing on the designed dimensions and earlier obtained technological parameters. The equivalent circuit for the MSM photodetector was simplified to the current source \( I_{ph} \), dark element capacitance \( C_{dark} \), and the series resistance \( R_s \). The values of those elements were calculated according to the equations given in Ref. 3, however, the values of HEMT transistor small signal circuit elements were calculated according to equations given in Ref. 4. The following values were determined: for the MSM detector – \( C_{dark} = 0.07 \) pF, \( R_s = 0.05 \) \( \Omega \); for transistor \( T_1 \); \( R_s = 0.74 \) \( \Omega \), \( R_d = 2.3 \) \( \Omega \), \( R_i = 2.2 \) \( \Omega \), \( C_{gs} = 2.54 \) pF, \( C_{gd} = 0.15 \) pF, \( g_m = 32 \) mS; for transistor \( T_2 \); \( R_s = 0.69 \) \( \Omega \), \( R_d = 2.5 \) \( \Omega \), \( R_i = 2.4 \) \( \Omega \), \( C_{gs} = 2.36 \) pF, \( C_{gd} = 0.14 \) pF, \( g_m = 29 \) mS. For both transistors it was assumed that: \( R_i = 10 \) \( \Omega \) and \( R_{ds} = 400 \) \( \Omega \).

Fig. 3. Topology of a) MSM2 photodetector, b) transistor T\(_2\) (dimensions in µm).

![Fig. 3](image)

Fig. 4. Simplified small signal equivalent circuits of a) MSM photodetector, b) HEMT transistor.

![Fig. 4](image)

Fig. 5. Simulated frequency response of the designed integrated photoreceiver for \( I_{ph} = 1 \) µA and different output load resistances \( R_L \).

![Fig. 5](image)
The frequency response obtained as a result of the performed simulations, executed for $I_{ph}$ current effective value of 1 µA, is shown in Fig. 5. The resulted bandwidth was about $f_{-3db} = 600$ MHz for the $R_L = 50$ Ω output load and $f_{-3db} = 550$ MHz with $R_L = 200$ Ω output load. To compare, the amplifying stage alone, at $U_{GS-T2} = 100$ µV, had frequency band: $f_{-3db} = 10$ GHz (1 dB gain) with $R_L = 50$ Ω output load and $f_{-3db} = 4$ GHz (9 dB gain) with $R_L = 200$ Ω output load.

Basing on the above mentioned results, one can conclude that the value of the resistor $R_1$ is one of the most important determinants of the designed circuit bandwidth. Since the photodetector capacitance was very small (0.07 pF), the dominant time constant is composed of the $R_1$ and the input capacitance $C_{gs}$ of the $T_2$ transistor which is quite large 2.5 pF because of large value of the gate width. If we assume that the resistor $R_1$ has the value of 50 Ω, than the frequency band of the photoreceiver is $f_{-3db} = 1$ GHz with $R_L = 50$ Ω output load, and $f_{-3db} = 900$ MHz with $R_L = 200$ Ω output load.

5. Conclusions

An integrated UV photoreceiver chip structure was designed and its technology on AlGaN/GaN layers was elaborated. A set of the proposed photolithography masks allows for experimental testing of ion implantation method versus mesa dry etch to provide electrical isolation in AlGaN/GaN monolithic circuits. The circuit contact pads allow for on-wafer measurements using a coplanar microwave probe. The designed structure can be used as an OEIC circuit or as a set of discrete devices HFETs and MSM. The results of the performed frequency response simulations showed that the designed circuit would operate in 1 GHz bandwidth with the gain of 9 dB.

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References