High-speed 1.3 -1.55 um InGaAs/InP PIN photodetector for microwave photonics

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Abstract. We have fabricated the 1.3-1.55 um PIN photodetector based on InGaAs/InP heterostructure. Measurement results of optical and electrical characteristics of PIN photodetector chip were the following: photoconductivity at 1550 nm was 0.65 A/W and internal capacitance was 0.025 pF. Microwave model of photodetector was developed and verified by measurements of scattering matrix. The implementation of broadband (up to 20 GHz) hybrid integrated matching and biasing circuit for high-speed photodetector is presented.

1. Introduction
Microwave (MW) photonics is a rapidly developing area for application in high-speed communication systems with 1.3–1.55 um spectral band corresponding to II and III transmission windows [1]. One of the key components of photonic links is a high-speed PIN photodetector (PD). In communication systems PD is destined to convert MW-modulated light into high-frequency electrical current, hence low PD capacitance \( C \) is required for high-speed operation [2-4]. Optimization of the PD structure (the use of PIN structure) and photoconductive operating mode (reverse-biased operating point) are commonly used to reduce the p-n junction capacitance \( C \) which is a function of active region area \( A \) and width of depletion layer \( W \) [5]. Another important characteristic of PD for communication systems is responsivity \( S \) (A/W) that also is a function of \( W \), therefore, maximum operating frequency is compromised by setting up parameters \( A \) and \( W \) to achieve low \( C \) and sufficient \( S \) simultaneously.

Accurate microwave characterization of PD chip is necessary for the proper design of the external matching circuit. Impedance matching (to system’s 50 Ohm) is required for effective data transmission as reverse-biased PD represents a high resistance (tens kOhm) for MW signal[6]. In this work we discuss fabrication of the PD heterostructure, modeling and measuring of optical and electrical characteristics of the 440\( \times \)370 um PIN PD chip with the PD active area of 18 um diameter. The design of matching and biasing circuit for photodetector operating up to 20 GHz is presented.
2. Experiment

Heterostructure for high-speed PIN PD for \( \lambda=1550 \) nm was grown by Molecular beam epitaxy (MBE) on a Riber49 ("Connector Optics", St. Petersburg). Growth of epitaxial heterostructure was implemented on semi-insulating indium phosphide substrate of 650 um thickness. The PIN photodiode heterostructure is shown on figure 1. The main part of light is absorbed by \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) layer of 0.8 um thickness. Dimension of absorption layer provides small tunneling time of generated charge carriers resulting in high-speed operation. At the same time high absorption coefficient of \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) provides sufficient photosensitivity. Several gradient layers are designed to match the lattice constant of contact layer, window layer (\( \text{In}_{0.52}\text{Al}_{0.48}\text{As} \)) and absorption layer.

| Layer | Thickness (um) | p-doping | n-doping |
|-------|----------------|----------|----------|
| Contact layer \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) | 0.1 | \( 1 \times 10^{19} \) | \( 1 \times 10^{18} \) |
| Gradient layer \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \gg \text{In}_{0.51}\text{Al}_{0.49}\text{As} \) | 288 | \( 1 \times 10^{19} \) | \( 1 \times 10^{18} \) |
| Window \( \text{In}_{0.51}\text{Al}_{0.49}\text{As} \) | 0.1 | \( 3 \times 10^{18} \) | \( 1 \times 10^{18} \) |
| Gradient layer \( \text{In}_{0.51}\text{Al}_{0.49}\text{As} \gg \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) | 288 | \( 1 \times 10^{18} \) | \( 1 \times 10^{18} \) |
| Absorption layer \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) | 0.1 | \( 1 \times 10^{18} \) | \( 1 \times 10^{18} \) |
| Absorption layer \( \text{In}_{0.52}\text{Al}_{0.48}\text{As} \) | 0.8 | \( 1 \times 10^{18} \) | \( 1 \times 10^{18} \) |
| Buffer layer \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) | 0.1 | \( 3 \times 10^{18} \) | \( 1 \times 10^{18} \) |
| Contact layer \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) | 0.5 | \( 1 \times 10^{18} \) | \( 1 \times 10^{18} \) | 55
| Substrate \( \text{InP} \) | 650 | \( 1 \times 10^{18} \) | \( 1 \times 10^{18} \) |

Figure 1. Heterostructure for PIN PD

Fabrication of PIN PD crystals included the following technological operations. Firstly, we formed ohmic contacts Ti / Au and AuGe/Ni/Au to epitaxial layers of InGaAs of p- and n-type conductivity, respectively, with subsequent burning at a temperature of 360°C. Then mesa-structures were formed by plasma-chemical etching BCl3/Ar. Mesa configuration was passivated using plasma-chemical deposition of silicon nitride. Contact pads were formed by sputtering of Ti/Au and enhanced by electroplating. The final step of fabrication of the PIN PD chip was the thinning of the substrate to 120 um and cutting of the operating plate to single PD chips. SEM image of PD active area is shown on figure 2 (a).

![Figure 2](image_url)

(a) Figure 2. (a) - SEM image of the PD active area; (b) – cross section of the PD

The coplanar waveguide structure of the PD contacts allowed direct probe measurements for MW characterization of crystal. We used vector network analyzer Keysight PNA N5242A together with MPI.
TS150 probe station to measure reflection coefficient form PD output and obtain the PD microwave parameters. Calibration on lumped coplanar waveguide standards (reference impedance, short line and open end) on AlN substrate helped to exclude measurements uncertainty connected with influence of crystal’s holder. Modeling of microwave part was conducted using equations based on distributed line theory together with 3D electromagnetic simulation based on method of moments.

3. Results and discussion

Measured PD chips were photosensitive in wide spectral range. Long-wave limit of the PDs was near 1,7 um, corresponding to In0,53Ga0,47As content of active layer. Maximum level of photosensitivity was 0,65 A/W and photosensitivity above 0,6 A/W was observed in 1400-1600 spectral range (see figure 3). Current-voltage measurements showed 100 nA dark current under 2 V reverse bias typically.

![Figure 3. Photosensitivity of the PD](image)

Figure 4 (a) shows reflection coefficient from PD crystals depicted on Impedance Smith Chart, imaginary part of PD impedance and parameters of small-signal equivalent circuit derived from the measurement. Commonly used equivalent small-signal electrical circuit representing parallel connection of intrinsic area capacitance $C_j$ and resistance under reversed bias $R_d$ placed in series with parasitic contact resistance $R_s$ was examined to describe MW properties of PD crystal [1]. Value of capacitance $C_j=25$ fF, which was previously calculated using equation (1) with modeled resistance $R_s=3$ Ohm and $R_d=10$ MOhm obtained from IV-curves fitted the measurement data, depicted on figure 4.

$$C_j = \frac{S(\varepsilon\varepsilon_0 N_d)}{2(\varphi+V)}, \quad (1)$$

where $S$ -p-n junction area, $\varepsilon$ – relative permittivity, $e$ - electron charge, $N_d$ – donor concentration in $i$-region, $\varphi$ - contact potential difference, $V$ – reverse bias voltage.

Maximum operating frequency of the PD chips can be evaluated using equation (2):

$$f_c = \frac{1}{2\pi(R_s+R_d)C_j}, \quad (2)$$

where $R_L$ – load resistance, $R_L = 50$ Ohm. Obtained crystals with values of capacitance $C_j = 25$ fF in combination with low resistance $R_s$ can provide up to 100 GHz bandwidth.
To realize the PD operation at MW frequencies we developed two circuits in microstrip realization. The two printed circuit board (PCB) layouts are designed for operation in circuits without (figure 5a) and with (figure 5b) requirements for decoupling MW and biasing channels. We used 0.25 mm Al₂O₃ ceramic substrate to design PCB operating up to 20 GHz. Layout of hybrid monolithically integrated circuits and their equivalent circuits are shown on figure 5.

Figure 4. (a) – Reflection coefficient from PD crystal shown on Impedance Smith Chart, imaginary part of PD impedance and parameters of PD equivalent small signal circuit. (b) – photo of the sample under probe station.

Figure 5. Layouts of PCB for MW matching and biasing PD crystal: (a) – without DC decoupling, (b) – with decoupling
We considered the contribution of wire bonding, microstrip discontinuities and microstrip-coaxial junction for accurate modelling of reflection coefficient of the matched and biased PD chips. The layout of the PCBs was optimized to minimize reflection coefficient from the PD output. The critical parameters for high-frequency operation were wire-bonding length and distance between PD crystal and resistor $R_i$ representing match load seen at output and providing broadband MW-matching. The use of thin-film resistor $R_1$ in combination with elements on microstrip line sections and broadband surface-mount components helped to achieve 20 GHz bandwidth. The results of modelling reflection coefficient and decoupling are shown on figure 6.

![Figure 6. Reflection coefficient R from MW output of PD and decoupling between DC and MW channel](image)

4. Conclusion
Fabricated PD chips has maximum photosensitivity 0.65 A/W at wavelength 1550 nm. The good agreement between simulated and measured parameters of PD for high-speed operation is shown. Hybrid monolithically integrated circuits of impedance matching and biasing for PD operating up to 20 GHz are developed.

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