A heterostructure for resonant-cavity GaAs p-i-n photodiode with 840-860 nm wavelength

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Abstract. A heterostructure for resonant-cavity p-i-n photodiode was grown by molecular beam epitaxy and consists of light-absorbing GaAs i-layer between p- and n-emitter layers of AlGaAs. The heterostructure employs Bragg reflector with more than 95% reflection coefficient at 840-860 nm wavelength. Photolithographic masks for chip fabrication were designed using optoelectronic and thermal phenomena simulation. Fabricated chips exhibit a bandwidth of 10 GHz and low dark current.

1. Introduction
Photodetectors (PD) are widely used in data transmission systems for an efficient conversion of microwave optical radiation into electrical signals without distortion [1]. The PD intended for this purpose must accurately reproduce the shape of the optical signal without introducing additional noise. GaAs semiconductor is widely used in the spectral range of 0.6 - 0.9 µm to fabricate high-speed PDs based on GaAs/AlGaAs heteroepitaxial structures. We chose two step mesa construction for multilayer heterostructure GaAs/AlGaAs grown on a semi-insulating GaAs substrate with a diameter of 76.2 mm. The use of such mesa construction with radiation input through the top contact layer of p ++ - GaAs has an undoubted advantage in terms of manufacturing technology, which is quite well developed and required for electrophysical and optical characteristics, product reliability and ensures the realization of good crystals.
Considering optoelectronic and thermal phenomena occurring in the heterostructure and the RPD chip at wavelengths of 840–860 nm simulation we obtained heterostructure showed in table 1 and considered following tasks:

- Optimization of the light-absorbing region thickness and width, based on i-layer of GaAs, surrounded by p- and n-layers of AlGaAs.
- Optimization of distributed Bragg reflector (DBR) layers thicknesses and Al$_x$Ga$_{1-x}$As concentration.
- Simulation of the distribution of thermal fields, the determination of the temperature of the active region and the most advantageous design (traditional or flip-chip), in terms of heat dissipation.

**Table 1. Parameters of a resonant-cavity p-i-n photodiode heterostructure optimizing for wavelength 840-860 nm**

| Layer name  | Layer material | Layer thickness, nm | Doping level, cm$^{-3}$ | Type   |
|-------------|----------------|---------------------|-------------------------|--------|
| Contact     | GaAs           | 30                  | 5×10$^{19}$             | p$^{++}$|
| Emitting p  | Al$_{0.2}$Ga$_{0.8}$As | 100                 | 1×10$^{19}$             | p      |
| Absorbing i | GaAs           | 170                 | -                       | i      |
| Emitting n  | Al$_{0.2}$Ga$_{0.8}$As | 315                 | 4×10$^{18}$             | n$^+$  |
| Stop-layer  | InGaP          | 4                   | 5×10$^{18}$             | n$^+$  |
| Contact     | GaAs           | 100                 | 5×10$^{18}$             | n$^{++}$|
| DBR         | Al$_{0.9}$Ga$_{0.1}$As/Al$_{0.12}$Ga$_{0.88}$As | 70/60×15 couples    | -                      | -      |
| Substrate   | GaAs           | 450 um              | Semi-isolated           | n      |

3. Optimization of RPD heterostructure

To simulate thermal and electrical processes using the finite element method we used COMSOL Multiphysics.

The simulation of p-i-n heterostructure band diagram with and without external bias showed that absorbing GaAs i-layer band gap is 1.42 eV. This fact allows i-layer to absorb radiation to 870 nm (figure 1). In order to reduce the absorption of light in the upper contact layer, the RPD heterostructure was designed so that the light field intensity in the contact layer was at a minimum.

![Figure 1. The edge of i-layer absorption.](image)

We calculated modulation bandwidth of the photodetector in dependence of the diameter of the first mesa. The capacity of the p − n junction depends on photosensitive region area and thickness of
$i$-layer. The thickness was determined by light intensity maxima locations in the absorbing layer. (figure 2).

![Figure 2](image)

Figure 2. Dependence of the refractive index and intensity on the thickness.

The calculation of the reflection coefficient $S_{11}$ of the equivalent matching scheme of chip, illustrated on figure 3, and microwave output for various capacities $p-n$ junction at frequencies up to 10 GHz (figure 4) made it possible to determine the maximum permissible capacitance at limited -10 dB bandwidth which was found to be 24 microns.

![Figure 3](image)

Figure 3. Equivalent matching scheme of RPD chip. 

![Figure 4](image)

Figure 4. The reflection coefficient $S_{11}$ of the equivalent circuit at various chip capacitances.

To increase the sensitivity in a wavelengths range of 840-860 nm and for carriers’ re-excitation in the $i$-layer we chose a DBR made of $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$ with thicknesses 70/60 nm, respectively. For reflection coefficient calculations was used the layer-by-layer method. Theoretical data were confirmed with the use of experimental setup for measuring photoluminescence and reflection RPM 2000. Both theoretical and experimental data are higher than 95% at 840-860 nm wavelengths and illustrated on figure 5.
Figure 5. Theoretical and experimental reflection coefficient from DBR.

The thermal distribution in the developed RPD chip was simulated taking into account the fact that the initial temperature is 293 K, the power of the heat source (absorbing i-layer) is from 5 mW to 150 mW (typical value of the power of the laser diode used in telecommunications) [4]. The obtained value of the maximum temperature of the i-layer, equal to 359 K (figure 6), indicates temperature change by 66 K. The thermal simulation showed that isometric contours do not leave GaAs substrate and do not contact with metal pads which indicates that there is no difference between traditional and flip-chip in terms of heat dissipation.

Figure 6. Temperature distribution in the main cross section of RPD chips.

4. Photolithographic masks
Development of the topology of RPD chip with CAD system allowed checking the compatibility of the layers on the individual topological structural elements of the chip. We took into account obtained optoelectronic and thermal phenomena in the chip and topological limitations imposed by the following manufacturing processes: photolithography, liquid etching, magnetron sputtering and dielectrics’ deposition. The working set of photolithographic masks for the manufacture of p-i-n RPD chips in accordance with the technological route consists of 6 templates. Fabrication was performed at the production facilities of OKB Planeta OJSC.
5. Measurement results
With application of developed heterostructure and photolithographic masks were created RPD chips with different photosensitive region widths. Samples with 30 um photosensitive region width demonstrated bandwidth of 10.1-10.3 GHz. Dark current value, which is one of the main noise sources in PD, was less than 5 nA. Studied chip with 30 um photosensitive region illustrated on figure 7.

Figure 7. Resonant-cavity GaAs p-i-n photodiode chip.

6. Conclusion
We studied optoelectronic and thermal phenomena that allowed us defining of the necessary parameters for development heterostructure of RPD which can find application in telecommunication information transmission lines corresponding to the first transparency window of quartz optical fiber. With use of 6 designed photolithographic masks and designed heterostructure were manufactured RPD chips with different diameter of light-absorbing region. Due to optimization of the light-absorbing region thickness and width, bandwidth of 10 GHz was achieved. Although, heat dissipation indicated that heat do not leave the substrate and do not reach areas where metal pads are located they still can be used for flip-chip coupling.

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