Research and development of high-speed on-chip photodetectors based on $A^{III}B^{V}$ heterostructures

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Abstract. This paper is aimed at the solution of the fundamental scientific and technical problem of research and development of high-performance optoelectronic devices designed for on- and inter-chip optical interconnecting in integrated circuits. Previously, we developed a laser with a double $A^{III}B^{V}$ nanoheterostructure and a functionally integrated optical modulator. The device is based on the principle of controlled spatial relocation of charge carrier density peaks within quantum regions and provides the generation of optical signals with high modulation frequencies. The detection of short laser pulses generated by the laser-modulator requires a technologically compatible on-chip photodetector with subpicosecond response time. To meet the given requirements, we propose a novel design of a high-speed photodetector that employs the same relocation principle as the laser-modulator. The photodetector contains a traditional p-i-n photosensitive structure and an orthogonally oriented control heterostructure. During the back edge of a laser pulse, the control heterostructure displaces the peaks of electron and hole densities into special low-temperature-grown regions with short lifetimes and low carrier mobilities. We developed the quantum mechanical numerical model of the photodetector with controlled relocation of carrier density peaks and estimated the duration of the photocurrent back edge.

1 Optical interconnections and photodetectors

The application of metal conductors is a traditional way of inter-element and inter-chip connecting in integrated circuits (ICs). However, the reduction in minimal topological dimensions to several tens of nanometres and less, and drastic increase in IC integration scale cause the appreciable decline in the parameters of metal interconnections (e.g. response time, channel capacity, energy and technological efficiency, reliability and noise immunity). Due to the physical scaling limits of traditional metal conductors, the development of next-generation interconnections for ICs is becoming an urgent problem.

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Nowadays, various methods for the solution of the IC interconnection problem are proposed [1-3]. Some of them consider the utilization of advanced physical principles and materials such as radio frequency networks on chips, optoelectronic links, super- and nanoconductors, carbon nanotubes and graphene for the creation of high-performance interconnections. Other methods are not so cardinal, and they are intended for the modification and optimization of traditional connecting techniques. In general, both approaches have advantages and disadvantages, and it is impossible to note the most preferable one.

An optoelectronic approach is aimed at the constructive and technological integration of optical interconnections with available and future hardware components of semiconductor electronics [4-6]. Typical optical interconnection for IC consists of a source of optical radiation, a high-speed modulator, an integrated waveguide, and a photodetector. At the current stage of technology, optoelectronic systems are suitable only for high-level inter-component connections on chips (e.g. inter-core connections in multi-core ultra-large-scale ICs) and inter-chip links because of their large scales in comparison with transistors. Nevertheless, the optoelectronic approach has several important advantages over its counterparts and provides the advancement of IC characteristics. During the past ten years, it demonstrated significant progress in the improvement of on-chip optoelectronic devices.

In papers [7-9], we proposed an injection on-chip laser with a double $A^{III}B^{V}$ nanoheterostructure and a functionally integrated optical modulator. The laser-modulator applies the principle of the controlled spatial relocation of charge carrier density peaks within quantum regions of valence and conduction bands [10] for the generation of amplitude- or frequency-modulated optical signals. Slow transients in the power circuit do not limit the peak modulation frequency of the device. This parameter is determined by the inertness of controlled relocation of carrier density maximums between the quantum wells of heterostructures. According to the results of numerical simulation, the peak modulation frequency of the lasers-modulators reaches the value of 1 THz and above.

To detect laser pulses generated by the laser-modulator, a technologically compatible photodetector with subpicosecond response time is needed. Previously, we performed the numerical drift-diffusion simulation of *p-i-n*, uni-travelling carrier (UTC) and Schottky barrier photodiodes [7, 11]. In compliance with the obtained results, the response time of traditional photosensitive structure exceeds several picoseconds and depends on multiple factors. The major one is the lifetime of charge carriers in the active region of a device before their recombination that is more than 1 ns for standard photosensitive structures. The usage of low-temperature grown (LT) $A^{III}B^{V}$ layers is the essential method of the carrier lifetime reduction in photodetectors. Compared to epitaxial materials grown at regular temperature, low-temperature epitaxial growth results in a dramatically shorter carrier lifetime and in a lower carrier mobility [12]. However, within classical designs of semiconductor photodetectors, LT layers negatively affect the amplitude of photocurrent and times of electron and hole transit through the active region. Consequently, the development of a fundamentally new photosensitive device is required.

2 Photodetector with controlled relocation of carrier density peaks

To improve response time and provide high sensitivity, we propose a novel design of a high-speed photodetector for optical interconnections in integrated circuits. The proposed device is called “a photodetector with controlled relocation of carrier density peaks” and employs the same principle as the lasers-modulators [10]. Fig. 1 and Fig. 2 show the cross-section of the photodetector with controlled relocation of carrier density peaks and the band diagram of its control heterostructure, respectively.

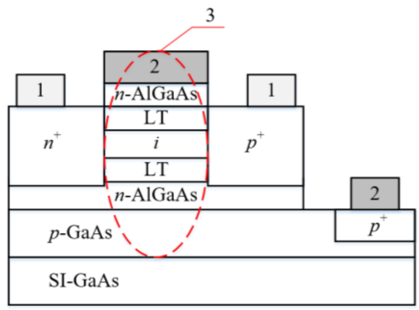

Fig. 1. The cross-section of the photodetector with controlled relocation of carrier density peaks: 1 – supply contacts; 2 – control contacts; 3 – control heterostructure.

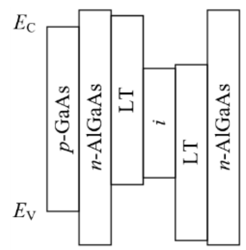

Fig. 2. The energy band diagram of the control heterostructure of the photodetector with the controlled relocation of carrier density peaks.

The photodetector with controlled relocation of carrier density peaks is based on traditional *p*-*i*-*n* structure (see Fig. 1). In comparison with conventional photodiodes, the proposed device contains an orthogonally oriented control heterostructure, which includes the lower *p*-*n* control junction *p*-GaAs/*n*-AlGaAs, first and second LT layers with short carrier lifetimes and low mobilities, thin absorbing *i*-region located between two LT layers, and upper Schottky control junction *n*-AlGaAs/metal (see Fig. 2). The direction of light propagation is normal to the plane of figures. In the operation mode, reverse and constant bias voltage is applied to supply contacts. The absorbing *i*-region has the narrowest bandgap in the whole heterostructure, and the laser radiation is absorbed only there.

During the leading edge of a laser pulse, the photodetector with controlled relocation of carrier density peaks works analogously to *p*-*i*-*n* photodiodes. Control voltage equals to zero, and the maximums of electron and hole densities are overlapped in the *i*-region. Immediately after the start of the pulse's back edge, a special control scheme with ultrashort response time generates a fixed voltage at the control contacts. The transverse electric field divides the peaks of carrier densities and shifts them to corresponding LT layers. Within that fast process, the total number of charge carriers in the wells remains nearly unchanged. Photogenerated electrons and holes get from the *i*-region with durable carrier lifetimes and high mobilities into the LT layers with short lifetimes and low mobilities. As a result, the photocurrent density sharply falls, and non-equilibrium electrons rapidly recombine in LT layers. Thus, the developed photodetector with controlled relocation of carrier density peaks maintains the advantages of p-i-n photodiodes and allows the shortening of photocurrent's back edge.

3 Quantum mechanical simulation

In order to simulate transients in the photodetector with controlled relocation of carrier density peaks, we implemented the one-dimensional quantum mechanical model based on the Schrodinger–Poisson equation system [13]. Within this numerical model, we addressed the processes only in the control heterostructure. Some simulation results are given in Fig. 3 and Fig. 4. The estimation of photocurrent density shown in Fig. 4 was performed with the use of semiclassical formulas.

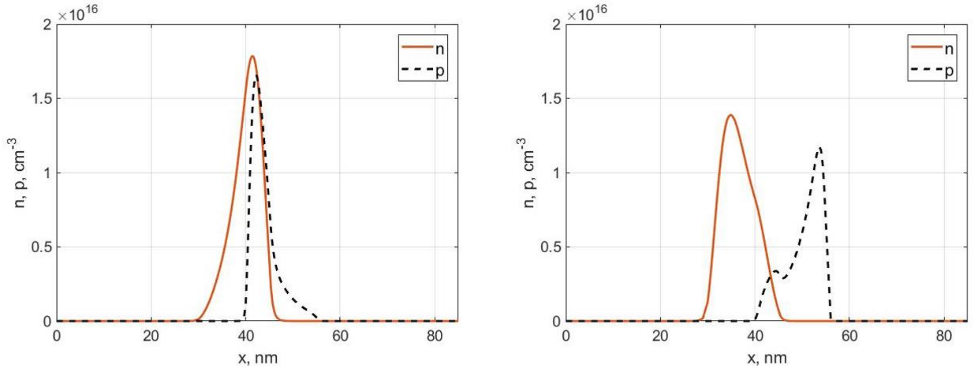

Fig. 3. The spatial overlap (left plot) and separation (right plot) of electron (*n*) and hole (*p*) density peaks in the photodetector shown in Fig. 1. The control voltage equals to 0 (leading edge of a laser pulse) for the left plot and to constant non-zero value (back edge of a laser pulse) for the right plot.

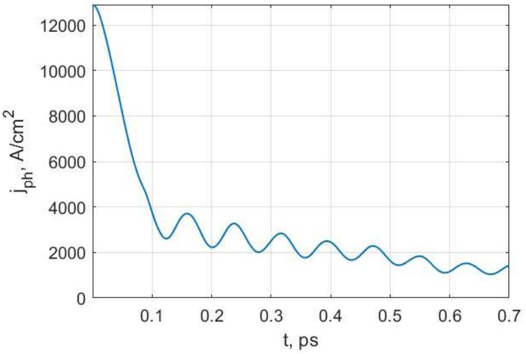

Fig. 4. The dependence of photocurrent density on time during the back edge of a laser pulse. This photocurrent flows through the supply contacts of the photodetector with controlled relocation of carrier density peaks.

According to the results shown in Fig. 4, the back edge of photocurrent pulse has two pieces. The first one has a steep slope and the duration of about 0.1 ps. It corresponds to the fast relocation of carriers into LT regions after the application of control voltage. The second piece is flat because of recombination and transport processes in LT layers.

4 Conclusions

Thus, we developed the promising type of photodetectors that utilizes the controlled relocation of carrier density peaks for the improvement of response time and sensitivity in comparison with widespread p-i-n photodiodes. To estimate the performance of the device, we realized the quantum mechanical model that was based on the Schrodinger-Poisson equation system. According to the results of numerical simulation, the duration of the steep piece of photocurrent's back edge is about 0.1 ps.

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