High-speed photodetector with controlled relocation of carrier density peaks

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Abstract. Nowadays, metal interconnections are near to the physical limit of their application in integrated circuits due to the continued scaling of transistors and an increase in the integration degree. An optoelectronic approach to the solution of this problem considers optical systems as advanced on- and inter-chip connections. Our previous papers were aimed at the development of an injection laser with a double A³B⁵ heterostructure and a functionally integrated optical modulator. Owing to the principle of controlled relocation of carrier density peaks within quantum regions, the laser-modulator can generate optical signals with terahertz modulation frequencies. To detect such signals, a technologically compatible photodetector with subpicosecond response time is needed. In this paper, we propose a novel design of A³B⁵ high-speed photodetector for optical interconnections in integrated circuits. It is based on the same relocation principle as the laser-modulator and includes a traditional p-i-n photosensitive junction and an orthogonal control heterostructure that displaces the peaks of electron and hole densities into special low-temperature-grown regions during the back edge of a laser pulse. We developed a numerical model of the photodetector with controlled relocation of carrier density peaks and estimated the duration of the photocurrent back edge.

1. Introduction

Nowadays, response time, channel capacity, reliability, noise immunity and other essential characteristics of inter- and on-chip metal interconnections are adversely affected by the scaling trends of integrated electronics. Because of this, the development of new interconnecting techniques for integrated circuits (ICs) is becoming an urgent research direction [1]–[4].

An optoelectronic approach treats the constructive and technological integration of on- and inter-chip optical interconnections with available and next-generation hardware components of ICs [5]–[7]. A conventional optical interconnection for ICs consists of an on-chip or an external source of optical radiation, a high-speed modulator controlled by a laser driver circuit, an integrated waveguide and a photodetector. Despite some limitations caused by the relatively large scales of the aforementioned devices in comparison with state-of-the-art transistors, the optoelectronic approach has important geometrical, design, parametric and technological advantages over its counterparts and provides the
appreciable advancement of IC characteristics. It demonstrated significant progress in the improvement of on-chip optoelectronic devices during the past ten years.

Previously, we proposed the concept of an injection laser with a double AlGaAs heterostructure and a functionally integrated optical modulator [8]–[10]. The device employs the principle of controlled relocation of carrier density peaks within specially shaped quantum regions of valence and conduction bands [11] for the generation of amplitude- and frequency-modulated optical signals. The terahertz modulation frequency of lasers-modulators is caused by subpicosecond time of controlled relocation of carrier density maximums between quantum wells of the modulator heterostructure. In contrast to typical semiconductor lasers, slow transients in the power circuit do not limit the laser-modulator performance.

The laser-modulator is an effective on-chip source of radiation for optical interconnections in ICs. However, the detection of laser pulses generated by the laser-modulator requires a technologically compatible AlGaAs photodetector with subpicosecond response time and high sensitivity. In papers [9], [12], [13], we simulated p-i-n, uni-travelling carrier (UTC) and Schottky barrier photodiodes using the drift-diffusion numerical model. The simulation results showed that the performance of photosensitive structures depends on the carrier lifetime in the active regions of the devices. With regard to high-field effects and standard values of the carrier lifetime in AlGaAs semiconductor materials (1 ns and more), the response time of traditional photodetectors exceeds several picoseconds, and it is not sufficient for our purpose.

2. Photodetector with controlled relocation of carrier density peaks

Low-temperature-grown epitaxial layers (LT-layers) are usually applied for the reduction in the carrier lifetime in semiconductor photodetectors. Compared to epitaxial materials grown at regular temperature, low-temperature epitaxial growth results in a dramatically shorter carrier lifetime and a lower carrier mobility [14]. Unfortunately, the introduction of LT layers into the classical on-chip photodetectors leads to the degradation of their key parameters such as the amplitude of photocurrent (or the sensitivity) and the time of carrier transit through the active region. Thus, the efficient implementation of the laser-modulator-based optical interconnections demands the development of a fundamentally new photosensitive structure.

In this paper, we propose a novel design of a photodetector for optical interconnections in ICs. Analogously to the laser-modulator, it utilizes the controlled relocation principle [11], which can improve the photodetector response time and sensitivity. Figure 1 shows the cross-section of the photodetector with controlled relocation of carrier density peaks and the energy band diagram of its transverse control heterostructure.

![Figure 1](image_url)

**Figure 1.** The photodetector with controlled relocation of carrier density peaks: the overall cross-section (a) and the band diagram of the control heterostructure (b). Cross-section (a) contains the following positions: (1) photosensitive $p^+\text{-}i\text{-}n^+$ junction; (2) supply contacts; (3) control heterostructure; (4) control contacts.
A horizontal $p^+ - i - n^+$ photosensitive structure is a major element of the photodetector with controlled relocation of carrier density peaks (see position 1 in figure 1(a)). Heavily doped $p^+$- and $n^+$-type regions are connected with supply ohmic contacts (position 2 in figure 1(a)). In the operation mode, reverse and constant bias voltage is applied to contacts 2. An absorbing $i$-type region is located between $p^+$ and $n^+$ regions and has the narrowest bandgap in the whole heterostructure. So, the laser radiation is absorbed only there. The direction of light propagation is normal to the plane of cross-section.

The presence of a vertically oriented control heterostructure (position 3 in figure 1(a)) is the distinctive feature of the photodetector with controlled relocation of carrier density peaks in comparison with usual photodiodes. The control heterostructure contains the following regions (see figure 1(b), left to right):

- a lower $p$-$n$ control junction $p$-GaAs/$n$-AlGaAs;
- a lower LT layer with short carrier lifetimes and low mobilities;
- a thin absorbing $i$-type region with durable carrier lifetimes and high mobilities;
- an upper LT layer that has the same features as the lower one;
- an upper Schottky control junction $n$-AlGaAs/metal.

The lower and upper control junctions are linked with control contacts (position 4 in figure 1(a)). The magnitude of control voltage equals to zero in all cases except for the back edge of a laser pulse.

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 thin $i$ region. Immediately after the start of the pulse’s back edge, a special control scheme with an 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 the corresponding LT layers. Within that fast process, the total number of charge carriers in the quantum 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 shortening of the photocurrent back edge.

3. Model, simulation methods and results

To simulate transients in the photodetector with controlled relocation of carrier density peaks, we developed a combined numerical model. On the one hand, the model is quantum mechanical because it describes relocation processes in the control heterostructure by the solution of the one-dimensional Schrodinger-Poisson equation system [15] along the $x$ axis (see figure 1(a)). On the other hand, the model applies the results of quantum mechanical calculations for the semiclassical estimation of photocurrent density versus time characteristic. The proposed combined model includes the following basic equations [15], [16]:

$$ j_{ph}(t) = \frac{qU}{LH} \int_0^H \left( n\mu_n + p\mu_p \right) dx; \quad (1) $$

$$ c = c_w \cdot \exp \left[ \left( \frac{1}{\tau_{L,c}} + \frac{1}{\tau_{R,c}} \right)^{-1} t \right]; \quad (2) $$

$$ c_w = \frac{m^* kT}{\pi \hbar^2} \sum_a \left| \Psi_{c,a}^2 \right| \ln \left[ 1 + \exp \left( \frac{\pm E_{k,c} \mp E_a}{kT} \right) \right]; \quad (3) $$
\[-i\hbar \frac{\partial \Psi_{c,a}}{\partial t} = \hbar^2 \frac{1}{2m_c} \frac{\partial^2 \Psi_{c,a}}{\partial x^2} - (V_c - q\varphi) \cdot \Psi_{c,a}; \tag{4}\]
\[
\frac{\partial}{\partial x} \left( \varepsilon \frac{\partial \varphi}{\partial x} \right) = -\frac{q}{\varepsilon_0} (p_n - n_n + N_D - N_A), \tag{5}\]

where \( c = n, p \); \( n, p \) are the electron and hole densities; \( n_n, p_n \) are the electron and hole concentrations obtained by the self-consistent solution of the Schrodinger-Poisson equation system without due regard to carrier recombination and transport along the \( y \) axis (see figure 1(a)); \( j_{ph} \) is the photocurrent density flowing through the supply circuit of the photodetector; \( x \) is the transverse coordinate (see figure 1(a)); \( \tau \) is time; \( \mu_n, \mu_p \) are the electron and hole mobilities; \( \tau_{r,c} \) is the charge carrier lifetime; \( \tau_{r,c} \) is the time of carrier transit along the \( y \) axis; \( q \) is the elementary electric charge; \( U \) is the supply voltage; \( L \) is the photodetector length (along the \( y \) axis); \( H \) is the photodetector height (along the \( x \) axis); \( m_c \) is the effective mass of charge carriers; \( k \) is the Boltzmann constant; \( T \) is the absolute temperature; \( \hbar \) is the Dirac constant; \( \alpha \) is the index number of the electron resonance level in the conduction band or the hole resonance level in the valence band; \( V_c \) is the heterostructure potential in the conduction or valence band; \( \varphi \) is the electrostatic potential; \( \Psi_{c,a} \) is the wave function of an electron or a hole; \( \varepsilon \) is the permittivity of a semiconductor; \( \varepsilon_0 \) is the permittivity constant; \( N_D, N_A \) are the concentrations of ionized donors and acceptors; \( E_{F,c} \) is the Fermi level for electrons (with positive sign) or holes (with negative sign); \( E_{\alpha} \) is the energy of the electron resonance level in the conduction band (with negative sign) or the hole resonance level in the valence band (with positive sign).

At the control contacts of the photodetector, we set the following Dirichlet boundary conditions for the Schrodinger-Poisson equation system:
\[
\Psi_{c,a} = 0; \tag{6}\]
\[
\varphi(t) = \frac{kT}{q} \ln \left( \frac{N_D - N_A}{2 \cdot n_i} + \left[ \left( \frac{N_D - N_A}{2 \cdot n_i} \right)^2 + 1 \right]^{\frac{1}{2}} \right) - \varphi_s + U(t), \tag{7}\]

where \( n_i \) is the intrinsic concentration; \( \varphi_s \) is the contact potential difference of the control junction; \( U(t) \) is the voltage applied to the control junction.

We solved the appropriate stationary problem by numerical methods for the evaluation of initial conditions (energy levels and wave functions of electrons and holes, distributions of the electrostatic potential and carrier densities at the reference time).

In equation (1), the photocurrent density \( j_{ph} \) is the product of the specific conductivity
\[
\overline{\sigma} = \frac{q}{H} \int_0^H (n\mu_n + p\mu_p) \, dx \quad \text{(averaged along the } x \text{ axis)} \]
and the transverse component of the electric field intensity \( \overline{E_y} = \frac{U}{L} \quad \text{(averaged along the } y \text{ axis)}. \)
We calculate the spatial and time distributions of carrier densities in two steps. At the first step, we compute carrier concentrations \( n_n \) and \( p_n \) by the self-consistent solution of the Schrodinger-Poisson equation system for electrons and holes. Here, finite difference coordinate and time grids are used, and the processes of carrier recombination and transport along the \( y \) axis are not taken into account. Then, at the second step, we refine concentrations...
with regard to carrier lifetimes $\tau_{Ln}$, $\tau_{Lp}$ in the heterostructure layers and to time intervals $\tau_{Tn}$, $\tau_{Tp}$ of electron and hole transit along the $y$ axis. The aforementioned processes determine the decrease in the densities of non-equilibrium photogenerated charge carriers during the back edge of a photocurrent pulse.

Figure 2 shows the spatial distributions of electron and hole concentrations in the control heterostructure of the photodetector with controlled relocation of carrier density peaks (along $x$ axis, see figure 1). To obtain these results, we utilized the combined numerical model (1)-(5) and the boundary conditions (6), (7). The control heterostructure contains a 30-nm lower control junction, a 10-nm lower LT layer, a 5-nm $i$-type absorption region, a 10-nm upper LT layer, and a 30-nm upper control junction.

Figure 2(a) corresponds to the instant just before the start of the back edge of the laser pulse. In this case, the control voltage is equal to zero, and the transverse electric field is quite weak. So, the peaks of carrier densities are overlapped in the thin $i$-region. Until the beginning of the back edge, the device is operated as a traditional $p-i-n$ photodiode. Strong longitudinal electric field in the active region of the $p^+-i-n^+$ structure separates the photogenerated charge carriers and accelerates them along the $y$ axis to the drift saturation velocity. Flowing through the supply circuit, non-equilibrium charge carriers induce a photocurrent.

Figure 2(b) demonstrates the distributions of electron and hole densities immediately after the end of relocation transient process during the back edge of a laser pulse. In the case being considered, the control voltage is equal to 1 V. The transverse electric field of the control heterostructure separates the peaks of electron and hole densities and relocates them to the lower and upper LT layers, respectively. The total number of charge carriers in quantum wells remains nearly unchanged during the fast relocation process. In the LT layers of the control heterostructure, carrier mobilities and lifetimes are significantly lower than in the $i$-region. A rapid change in carrier mobility and recombination rate leads to faster relaxation of the photocurrent in the supply circuit as compared to conventional $p-i-n$ photodiodes.

**Figure 2.** The spatial overlap (a) and separation (b) of electron ($n$) and hole ($p$) density peaks in the photodetector with controlled relocation of carrier density peaks.

Figure 3 shows the shape of the back edge of the photocurrent, which flows through the supply circuit of the photodetector with controlled relocation of carrier density peaks. According to the curve, the back edge of the photocurrent pulse has two parts. The first one has a steep slope and a duration of about 0.1 ps. It corresponds to the fast relocation of carriers into LT regions after the application of the control voltage. The second part is gently sloping because of further recombination and transport processes in the LT layers. The oscillation of the current density is caused by the reflection of electron and hole wave functions from the heterointerfaces in the transverse direction, the superposition of reflected waves and the corresponding changes in the carrier densities.
4. Conclusions

Thus, we proposed a novel design of a high-speed photodetector based on the principle of controlled relocation of carrier density peaks within specially organized quantum regions of the valence and conduction bands. To improve the back-edge performance of the $p-i-n$ photosensitive structure, we introduced a specialized control heterostructure that provides fast relocation of photogenerated carriers to the LT layers with low mobility and lifetime under the influence of a transverse electric field. In the developed photodetector, the duration of the photocurrent back edge depends on the subpicosecond time of relocation, but not on slow cleaning-out of non-equilibrium charge carriers by the electric field of the $p-i-n$ structure. The LT layers are separated from the absorption region of the $p-i-n$ structure, and their features do not affect the leading-edge performance of the device. We implemented a one-dimensional numerical model based on the Schrodinger-Poisson equation system in order to estimate the duration of the photocurrent back edge.

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