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Injection Laser with a Functionally Integrated Frequency Modulator Based on Spatially Shifted Quantum Wells

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Abstract—A method for designing injection lasers with functionally integrated optical-radiation frequency modulators based on spatially shifted quantum wells in conduction and valence bands is proposed. The structure and variants of band diagrams of functionally integrated laser modulators are considered. It is shown that, in the proposed nanoheterostructures, maximum modulation frequencies are determined by the time of controlled relocation of charge-carrier density maxima in quantum domains and correspond to the terahertz range.

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One of the problems in improving integration density of up-to-date ultra-large-scale integration circuits (ULSICs)—in particular, increasing the number of cores on crystals—is the insufficiently high efficiency of the available metal intercore joints, which do not longer meet the ever-increasing requirements for speed, power efficiency, and interference immunity. Specialists of leading companies see a solution to this problem primarily in the use of optical commutation integral circuits; one of the problems of developing these integral circuits is implementation high-speed optical sources and modulators, as well as their integration on a crystal using traditional semiconductor technologies [1, 2].

In up-to-date optical-commutation integral circuits, amplitude modulation is widely used, i.e., external modulation that employs modulators and internal modulation based on control over laser-pumping current density [3]. Dynamics of modulation based on control over pumping current density is governed by transient processes in the laser-feed circuit, which limits the maximum modulation frequency. External modulators also do not necessarily meet speed requirements; they are, as a rule, based on materials that make it impossible to produce them in the course of the same manufacturing process as integral semiconductor structures [4].

A concept of designing ULSICs that joins cores produced using silicon technologies with an optical commutation system based on materials of $A^{III}B^{V}$ group was proposed in [5, 6] as a possible approach to solving the above-mentioned problem; this system can be implemented in a single manufacturing process. A functionally integrated nanostructure that combines an optical source and an optical modulator is proposed as the key component of these optical commutation systems. In this nanostructure, amplitude modulation is implemented by controlled relocation of charge carrier density maxima in quantum domains of conduction and valence bands with definite configurations [6, 7]. Modeling results show that, in these laser modulators, modulation frequency can reach a few terahertz [4, 6].

Functionality of optical commutation integral circuits can be widened ever more by using not only amplitude, but also frequency modulation of laser radiation. For example, organic materials with bistable photochromic molecules, the properties of which change under the effect of photons with a definite wavelength, have found wide application as the base of molecular electronic components. Synthesis of novel photochromic organic materials opens prospects for developing integral molecular electronic devices with unique characteristics, which cannot be achieved in the framework of the current quantum-electronics paradigm [8]. However, such devices cannot be developed without matching of the main parameters of bistable organic molecules with characteristics of frequency-modulated integral laser sources, which control state of these molecules or molecular ensembles. This mainly concerns the maximum modulation frequency of a laser beam.

The aim of this work was to develop a method for designing optoelectronic devices of a new class, i.e., "laser triodes" or injection lasers with frequency modulators, which are functionally integrated into a single nanoheterostructure to ensure frequency modulation of stimulated radiation in the terahertz range.

With allowance for the use of two-level logic in digital integral circuits, it is reasonable to ensure a spectrum of a modulated optical signal with two maxima, i.e., controllable changing laser radiation wavelength between definite values λ_1 and λ_2, one of which corresponds to logical zero and the other to logical unity.

The proposed method for designing high-speed injection lasers with functionally integrated frequency modulators is based on the following principles:

(1) an injection laser modulator is a semiconductor nanostructure, in which degenerate *p–n* junction domains having corresponding ohmic (feed) contacts are functionally integrated with a frequency modulator heterostructure having supplementary (control) contacts and specially configured as a system of quantum wells;

(2) a definite pumping current is assigned in the laser-feed circuit; with the transient process completed, this pumping current ensures an inverse population, as well as a total number of electrons and holes in quantum wells of the active domain, that remains unchanged with time;

(3) in the frequency modulator nanoheterostructure functionally integrated into the injection laser, quantum wells of the conduction zones are spatially shifted so that, at one direction of control field, spatial superposition of maxima of electron and hole densities in quantum wells separated by a forbidden band with width E_{G1} and generation of laser radiation with wavelength λ_1 occur and, at the opposite direction of control field, spatial superposition of maxima of electron and hole densities in quantum wells separated by a forbidden band with width E_{G2} and, correspondingly, generation of laser radiation with wavelength λ_2 occur;

(4) at a constant level of injection of electrons and holes into the laser active zone, the total number of charge carriers in quantum wells remains almost invariable when the direction of the control field changes. As a result, the maximum laser-beam modulation frequency is determined by duration of field-controlled relocation of maxima of electron and hole densities in quantum wells of conduction and valence zones rather than by relatively inertial processes of accumulation and discharge of charge carriers in the laser active zone; according to numerical modeling results [4, 9], the duration of this relocation is (2.0–0.8) $\times 10^{-13}$ s depending on parameters of quantum wells, which corresponds to the terahertz-frequency band; and

(5) with allowance for the fact that the optical spectrum of the functionally integrated laser modulator contains radiation maxima at wavelengths λ_1 and λ_2, the resonator length should be a multiple of both $\lambda_1/2$ and $\lambda_2/2$.

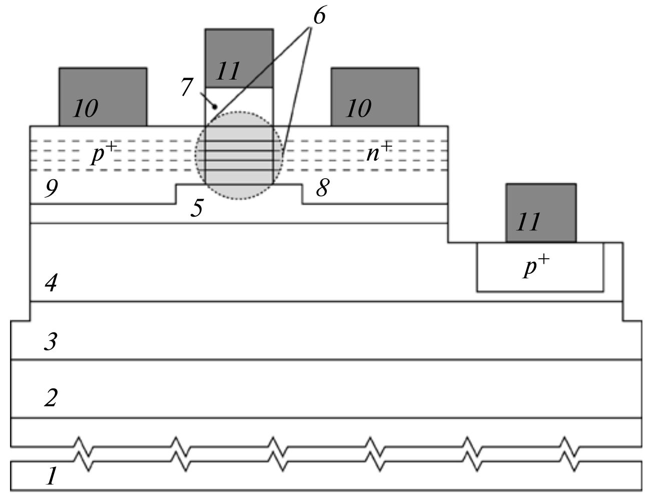

Fig. 1. Structure of an injection laser with a functionally integrated frequency modulator: (*1*) silicon substrate, (*2*) buffer gradient GaAsP layer [10], (*3*) semi-insulating GaAs, (*4*) *p*-GaAs, (*5*) *n*-GaAs, (*6*) frequency-modulator nanoheterostructure, (*7*) *n*-GaAs, (*8*) injecting n^+ domain, (*9*) injecting p^+ domain, (*10*) feed contact, and (*11*) control contact.

Based on the proposed design method, we developed a structure of a high-speed injection laser with a functionally integrated radiation-frequency modulator (Fig. 1).

One of the key problems in process implementation of this structure is to grow single-crystal GaAs layers on a silicon substrate. A number of methods are available for solving this problem. In the structure presented in Fig. 1, this is achieved by using a buffer gradient GaAsP layer (Fig. 1, item *2*). According to data from [10], gallium phosphide (GaP) and silicon (Si) have fairly close lattice parameters (the difference is 0.37%), which makes it possible to form a layer with gradually increasing concentration of As in GaAsP solid solution and, at definite thickness of this buffer layer, to ensure transition to single-crystal GaAs.

Unlike traditional laser diodes with a vertical structure, in the proposed laser modulator, high-doped injecting domains with electron and hole conductivity (Fig. 1, items *8* and *9*) have a horizontal mutual arrangement and are separated by a vertical nanoheterostructure of a functionally integrated frequency modulator (Fig. 1, item *6*). In the course of process implementation of the laser modulator, this specific feature of the structure can lead to a decrease in gradients of concentrations of doping impurities at interfaces between the modulator active zone and high-doped n^+ and p^+ domains, which should be considered during designing. With allowance for the fact that, owing to constant pumping current, the total number of charge carriers in the laser active zone remains unchanged and is almost independent of the direction

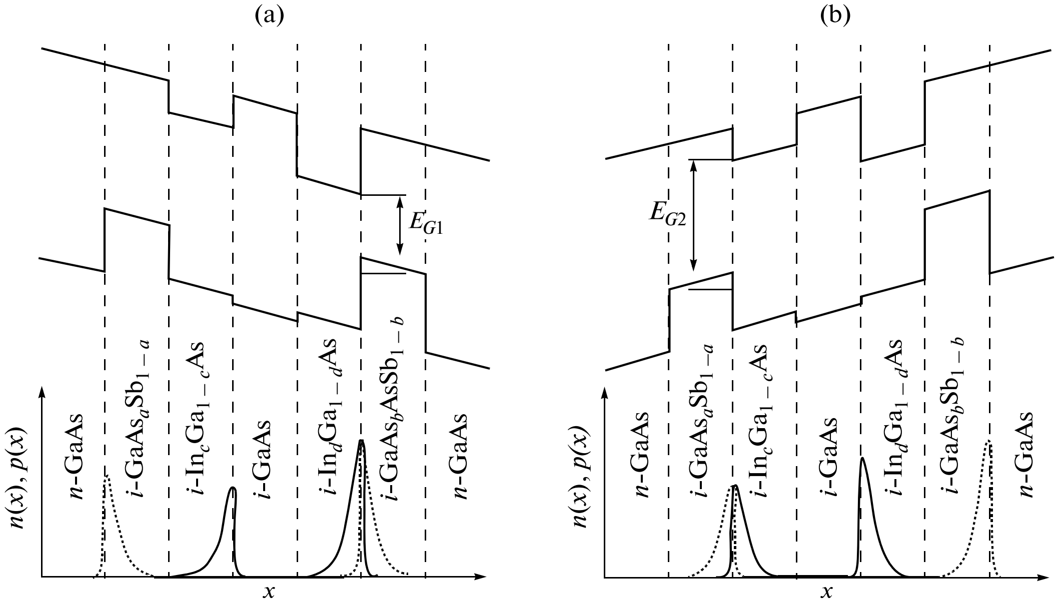

Fig. 2. Band diagrams of (a) first and (b) second versions of frequency modulator nanostructure and corresponding distributions of (solid lines) electron concentration and (dashed lines) hole concentration at opposite directions of control field.

of transverse control field, in this case, the maximum modulation frequency is mainly limited by lag of controlled relocation of carriers within quantum domains of the modulator. The frequency modulator, together with the injection laser itself, is a functionally integrated nanoheterostructure and can be produced in the course of a process that also employs traditional manufacture operations.

According to the proposed method for designing functionally integrated laser modulators, we developed basic variants of frequency modulator nanoheterostructures (Fig. 1, item *6*) with band diagrams and corresponding distributions of electron concentration $n(x)$ and hole concentration $p(x)$ for opposite directions of the control electric field and constant pumping current schematically presented in Fig. 2.

According to the band diagrams, the change in the direction of the control electric field results in migration of maxima of electron and hole densities toward opposite heteroboundaries of quantum wells. Spatial shift of quantum wells in the conduction zone with regard to quantum wells in the valence zone leads to spatial superposition of maxima of electron and hole densities in domains separated by forbidden bands with width of E_{G1} or E_{G2} depending on the direction of control field at constant pumping current. As a result, optical radiation with wavelength λ_1 or λ_2, respectively, is generated, i.e., frequency modulation of the laser beam occurs during its formation.

Since, in the course of modulation, the pumping current remains unchanged, the maximum modulation frequency is not limited by relatively inertial processes in the laser-feed circuit, but is determined by the duration of controlled relocation of maxima of electron and hole densities in spatially shifted quantum domains; according to numerical modeling results [4], this makes it possible to achieve terahertz modulation frequencies.

In the version of the modulator nanostructure shown in Fig. 2a, conduction and valence bands have two spatially shifted quantum wells each. In the version presented in Fig. 2b, adjacent quantum wells in the conduction band are united in a single quantum domain. In these versions of frequency modulator nanostructures, spatial shift of quantum wells is achieved by using second-type heterojunctions based on $In_aGa_{1-a}As$ and $GaSb_bAs_{1-b}$ semiconductor solid solutions. Different widths of forbidden bands at boundaries of second-type heterojunctions, which ensures frequency modulation of the laser beam in the course of its formation, are achieved by selecting the component composition of semiconductor solid solutions, i.e., constants *a* and *b*.

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