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Coherent transients in semiconductor nanostructures as the base of optical logic operating

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Abstract. The idea of the design is proposed for the photonic quantum gates (PG) with their input/output properties based on nonlinear optical dynamics of 2D arrays of two-level systems (TLS) in the resonance field of coherent optical pulses. As a particular example of the 2D medium with functions of the PG, we consider the GaAs/AlGaAs-based 2D excitonic structures. By methods of femtosecond chronopolarimetry of delayed photoreflection, we have studied the energy and phase relaxation rates and the biexciton binding energy in these structures and have shown that the GaAs/AlGaAs MQW can serve as a good basis for building the PG.

Fundamental limitations for speed of electronic computers stimulates physicists to searching for alternate ways of implementation of computational operations. As the most promising trend is considered replacement of electrical methods of information processing by optical ones, characterized by extremely high bandwidth and possibilities of global parallelism of calculations [1]. At the same time, a serious problem in development of optical computer is related to the absence of constructive ideas about the ways of implementation of the optical logical operations that could be competitive, in terms of their speed, smallness of energy consumption, and possibilities to be miniaturized, with contemporary elements of micro- and nanoelectronics [2].

In this communication, based on analysis of optical dynamics of the epitaxial semiconductor heterostructures, we propose a specific method of the photonic logical element, capable of overpassing, in its main parameters, not only the present-day but also anticipated potentialities of electronic circuits. The photonic logical element is referred to a structure with two stable states capable of passing from one state to the other under the action of combination of the input (controlling) light pulses. The output light signal carries information about final state of the logical element, with the shape of the input and output signals being standardized. The latter requirement is related to necessity to perform several successive computational operations, with the output signal of the preceding element being the input for the subsequent one.

The operation of the proposed logical element is based on properties of resonance ensemble of two-level systems, which can be inverted by a short light pulse (by the so-called pi-pulse [3]). As can be found by use of the Maxwell–Bloch equations [4], for the case of exact resonance and with no allowance made for relaxation the inverted ensemble is capable of emitting the secondary light pulse virtually identical to the exciting one. If to ascribe unity to the inverting light pulse and zero to the pulse of essentially smaller amplitude, such an ensemble can be used to build a logical element of optical computer. This conclusion is confirmed by the results of numerical calculations of the response of ensemble of two-level systems to the pulse with the small amplitude as shown in Fig. 1. It follows herefrom that weak pulses of standard shape can be used to read out the state of the ensemble, and the result of the read-out will have the form of a logical light pulse.

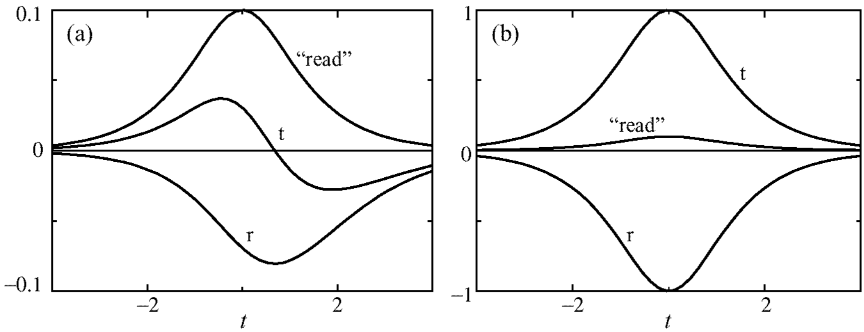

Fig. 1. The readout of the TLS in state 1—(a), and 2—(b).

Thus, the analysis of dynamics of ensemble of two-level systems in the field of coherent light pulses confirms fundamental opportunity to use the ensemble for implementation of all-optical logical operations. We have to estimate, however, to what extent the approximations made in analysis are justified for real physical systems.

The first serious assumption, was about exact resonance between the frequency of the light oscillations and eigenfrequency of each two-level system of the ensemble. This means, in fact, that the spread of eigenfrequencies of the two-level systems (i.e., the inhomogeneous broadening) should be essentially smaller than the Rabi frequency. For quasi 2D-structures the Rabi frequency is proportional to the product of the dipole moment of two-level systems on the concentration of systems. So, to meet the above condition, one has to use two-level systems with allowed electric-dipole transitions and with greatest concentration. This is the reason why the free excitons in quantum-confined semiconductor structures are considered as the most promising objects. The dipole moment of optical transitions in such structures is the greatest, while the concentration is equal to the number of sites of the crystalline lattice in the layer [5].

The second important assumption — ignoring relaxation processes — can be considered justified if the switching time of the cell determined by the light pulse width is much smaller than relaxation times of the ensemble. From this point of view, the high energy of the exitonphonon coupling in quasi-2D heterostructures is also a merit.

In addition, a fundamental question arises about applicability of two-level approximation to the excitons, since the exciton energy structure, in a perfect crystal, represents a set of equidistant levels. In real crystals, this is not the case due to exciton–exciton interaction, and if the energy of this interaction essentially exceeds the energy of excitations with photonic field, the two-level approximation can be considered justified.

To make clear, to what extent parameters of real heterostructures can satisfy all the above conditions, we have performed experimental study of nonlinear optical dynamics of HH-excitons in a sample of standard quality grown by the MBE technique.

The samples under study were 20-period superlattices GaAs/$Al_{0.3}Ga_{0.7}As$ with 7-nm thick GaAs and AlGaAs layers grown on the GaAs (100) plane without growth interruption on heteroboundaries. We studied dynamics of the pulsed differential photoreflection in the pump-probe configuration. In this scheme, the sample is successively subjected to action of two short optical pulses (pump and probe) with a time delay of t_d , and the probe beam amplitude is measured as a function of the time delay.

The pump and probe beams were formed by splitting the output pulses of a tunable Ti:sapphire laser. The pulse width was 70 ps. The frequency of the laser beam was tuned in resonance with that of the HH-exciton transition of the structure under study. The probe

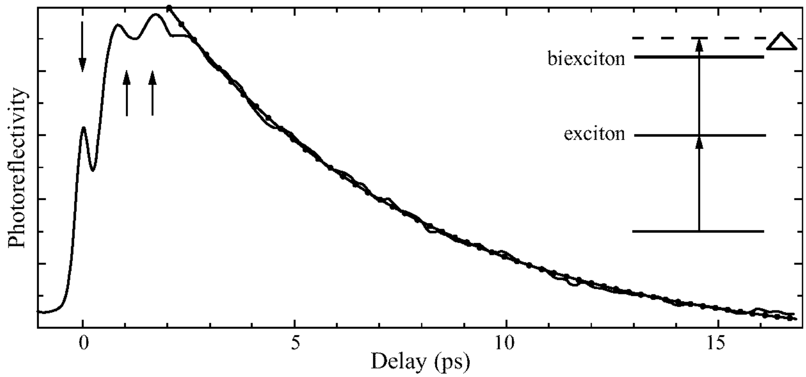

Fig. 2. Dynamics of the induced dichroism in the resonance delayed photoreflection of the HH-excitons.

beam was transmitted through an optical delay line, and then both beams were converged on the sample by means of a thin lens ($f = 20$ cm).

Dependence of the signal amplitude on the time delay t_d is shown in Fig. 2. The main signal is associated with two-photon coherent scattering by the population inversion of the HH-excitons, and its shape reflects population dynamics of the excitonic states. Exponential approximation of trailing edge of the pulse yields the relaxation time $\tau = 6 \cdot 10^{-12}$ s. The detailed analysis shows that the measured time is predominantly related to radiative recombination of the excitons. The above value well agrees with theoretical estimates of the radiative lifetime of free excitons in quasi-2D GaAs/AlGaAs structures [5].

In the experiments with time-integrated signal detection, the presence of the dephasing processes should be accompanied by a decrease of the detected amplitude of the two-photon coherent scattering. As has been shown experimentally, the signal from the sample under study remained virtually the same up to 25 K and varied linearly with the pump power density. This means that the phase relaxation rates related to the exciton–phonon and exciton–exciton scattering were essentially lower than the radiative decay rate of the excitons.

In Fig. 2, along with the main signal, one can see, at the initial stage of the pulse, several periods of oscillations with the frequency close to 10^{12} Hz. As is known [6], the source of such oscillations in the coherent signal are the beats between two transitions with close frequencies. At the same time, analysis of the luminescence and absorption spectra of the structure under study has shown no splitting near the energy 4 meV, corresponding to the observed modulation frequency. Therefore, the only source of the oscillating signal can be quantum beats between the biexciton and two single-exciton states [7]. This means that the inter-exciton coupling energy equals 4 meV and exceeds essentially the exciton–photon interaction energy 0.1 meV determined from the measured radiative decay rate.

Thus, the standard GaAs/AlGaAs heterostructures, in terms of their relaxation parameters, correspond fairly well to the requirements mentioned above. The main obstacle that does no at allow one to implement, with their help, photonic logical operations is too large inhomogeneous broadening 5 meV. However, according to the literature data [8], contemporary level of the MBE technology allows one to decrease the inhomogeneous broadening in structures of this type at least to 200–300 μV, i.e., down to the value comparable with the radiative broadening. Such high-quality structures are, in principle, already suitable for implementation of a planar matrix of photonic logical elements operating in parallel. The transverse size each element, determined by the light-wavelength, will lie in the range of 1 μ, i.e., about 10^6 elements can be arranged inside the area 1 mm^2. The clock frequency, for these elements, is limited only by the exciton relaxation rate and can approach 10^{11} Hz, with the switching energy lying around 10^{-16} J. In terms of the relation between these parameters, the photonic logical elements can exceed, by several orders of magnitude, the performance of electronic systems. It is important also that the switching energy, in such elements, is not converted into heat, as in all electronic circuits, but rather remains in the system in the form of a logical signal.

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