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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

LAMP SERIES REPORT
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MODELING OF NOVEL LIGHT SOURCES BASED ON ASYMMETRIC HETEROSTRUCTURES

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ABSTRACT

For asymmetric quantum–well heterojunction laser sources, processes of carrier injection into quantum wells are considered. In contrast to ordinary quantum–well light sources, active layers in the novel nanocrystalline systems have different thicknesses and/or compositions. In addition, wide–band gap barrier layers separating the quantum wells may have a linear or parabolic energy potential profile. For various kinds of the structures, mathematical simulation of dynamic response has been carried out.

MIRAMARE - TRIESTE
July 1995

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Preface

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1 Introduction

Investigations in the field of physics of nanodimensional systems are mainly carried out in three directions: the study of the effect of dimensional quantization, the search for suitable materials and ways of controlling their properties, and the development of a new generation of micro- and optoelectronic components. Nanocrystalline semiconductor elements exhibit unique properties.

The present paper concerns a new type of nanoscale semiconductor systems based on asymmetric heterostructures having a set of quantum wells (QWs) differing in width and composition and a modified energy profile in barrier layers. Previous authors reported the realization of laser action in asymmetric heterostructures at two wavelengths [1]. We have shown the possibility of attaining, in modified asymmetric heterostructures, regimes of bistable switching-on [2] and generation of regular radiation pulses [3].

In this paper, the behavior of nonuniform excitation of the QWs has been considered. Tunnelling processes are taken into account within the framework of a quasi-classical approach and estimates have been made for the ballistic transfer current. The results of calculations have been evaluated for an experimentally realized system [1]. Lasing regimes of modified asymmetric QW lasers are described too. Spontaneous and induced recombination rates and gain spectra have been calculated in a model with the $\vec{k}$-selection rule. Calculations were performed for the $GaAs$ - $Al_xGa_{1-x}As$ system [4], [5].

2 Carrier Transfer in Asymmetric Heterostructures

The basic equations include Poisson's equation for the electrostatic potential φ and the equations of continuity for the electron j_e and hole j_h current densities [6]. Under the assumption of quasi-equilibrium in semiconductor energy bands, expressions for the currents are of the form

$$j_e = \mu_e n \frac{\partial F_e}{\partial z}, \qquad j_h = \mu_h p \frac{\partial F_h}{\partial z}, \tag{1}$$

where z is the co-ordinate along the quantization axis, n and p are the concentrations, F_e and F_h are the quasi-Fermi levels, μ_e and μ_h are the mobilities for electrons and holes respectively.

2.1 Current Carrier Tunnelling

As a rule, in the active and barrier layers there are portions where the energies of the conduction band bottom E_c and of the valence band top E_v change rapidly with the z-co-ordinate. Because electron wave functions penetrate into the barriers, the resulting tunnel transfer through the potential barriers can make an essential contribution to the current. To take into account the current carrier tunnelling, we use the quasi-classical approach [7].

Consider for certainty the state in the conduction band with a zero z-component of the quasi-momentum at point z_0. Since the quasi-momentum components in the plane of the QW layers do not depend on the z-co-ordinate, in the barrier region where $E_c(z) > E_c(z_0)$ the state under consideration will be characterized by an imaginary z-component of the quasi-momentum, i.e., it will be decaying. The contribution of the carriers, the

z-component of the quasi-momentum of which becomes imaginary in the interval $[z_0, z_0 + \Delta z]$, to the total density of tunnel states can be written in the form

$$\Delta n_t(z, z_0) = \int_{E_c(z_0)}^{\infty} [\rho(E - E_c(z_0)) - \rho(E - E_c(z_0 + \Delta z))] \times \\ \times f(E_c(z_0), F_e(z_0))dE \times exp\left(i \int_{z_0}^{z} p_z(z')dz'\right), \tag{2}$$

where $\rho(E - E_c(z))$ is the volume density of states; $p_z(z) = \sqrt{2m_z (E_c(z_0) - E_c(z))}$ is the quasi-momentum z-component; m_z is the longitudinal effective mass; $f(E_c, F_e)$ is the Fermi-Dirac function. The difference in the volume densities in Eq.(2) determines the arising tunnel density of states, and the Fermi-Dirac function takes into account the probability of their population. In order to obtain the total tunnel density of carriers at point z, it is necessary to sum up the contributions given by Eq.(2) of all parts of the barrier where the conduction band edge energy is lower than at the sought point:

$$n_t(z) = \sum_{E_c(z_0) < E_c(z)} \Delta n_t(z, z_0). \tag{3}$$

Then, the obtained thus tunnel density of carriers enters into Poisson's equation and into the current continuity condition equally with the volume concentration of carriers. For the structures under further consideration the value γ_e of the ratio of the tunnel carrier density to the volume concentration is near to unity in the center of the barrier layer between QWs. Thus, about a half of the electron current transfer between QWs is being of tunnelling character.

2.2 Ballistic Transfer of Carriers

If QWs are inhomogeneously excited, the electron or the hole quasi-Fermi level changes in a barrier region between the QWs significantly. Therefore, the expression for the corresponding current from Eq.(1) must be modified. When the barrier layer thickness is smaller than the electron mean free path, ballistic throw-over plays a significant role [8]. In the case of purely ballistic transfer, the current over the barrier arises as a result of imbalance in high-energy electron concentrations on either side of the barrier:

$$j_{21} = e\, \bar{v}_z\, N_C \left\{exp\left(\frac{F_{e2} - E_{cm}}{kT}\right) - exp\left(\frac{F_{e1} - E_{cm}}{kT}\right)\right\}\left(1 + \gamma_e\right). \tag{4}$$

Here $\bar{v}_z = \sqrt{kT/2\pi m_z}$ is the average projection of the thermal velocity on the z-axis; E_{cm} is the maximum value of the conduction band edge energy in the barrier; N_C is the effective state density in the central region of the barrier; F_{e1}, F_{e2} are the quasi-Fermi levels at the opposite sides of the barrier; T is the temperature; γ_e takes into account the contribution of tunneling. A similar dependence of the current over a barrier on the quasi-Fermi levels can be also described by using the general Eq.(1) with the restricted mobility.

It is useful to express the current j_{21} in terms of variables determining the excitation level of QWs. The quasi-Fermi level for holes in the region between the QWs is practically constant. In the central part of the barrier the relative position of the valence band edge and the quasi-Fermi level for holes remains unaltered with a change in the excitation level.

Consequently, an increase in the difference in the quasi-Fermi levels for electrons and holes ΔF in the barrier layer is fully due to change in the quasi-Fermi level for electrons. Then, assuming j_{b0} to be the parameter of the structure, we can write the expression for j_{21} in the form

$$j_{21} = j_{b0} \left\{ exp\left(\frac{\Delta F_2}{kT}\right) - exp\left(\frac{\Delta F_1}{kT}\right) \right\}. \quad (5)$$

Expression (5) can readily be generalized for calculations of the leakage current from QWs to emitters if the distribution of minority carriers in the emitters is nondegenerate. Assuming that in the parts which are far away from the active region $\Delta F = 0$, we obtain for the current leakage from well i the relationship

$$j_{li} = j_{l0} \left\{ exp\left(\frac{\Delta F_i}{kT}\right) - 1 \right\}, \quad (6)$$

where j_{l0} is the structure characteristic parameter.

3 Structures with a Controllable Radiation Spectrum

To check the suitability of the developed mathematical model, we have performed calculations for structures studied experimentally [1]. These structures in the $GaAs$ – $Al_xGa_{1-x}As$ system contain two QWs (1 and 2) with the width of 8 and $16nm$ and the Al mole fraction $x_1 = 0$ and $x_2 = 0.08$, respectively, that are separated by a barrier with the $15nm$ width and the Al composition $x_b = 0.3$ (Fig.1). The lasing regime was realized at two wavelengths.

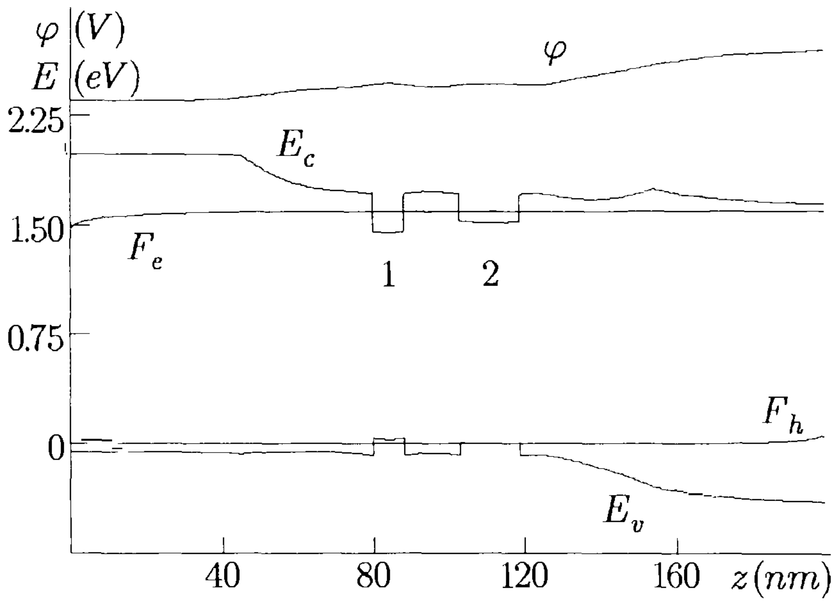

Figure 1: Band diagram of the asymmetric dual QW laser under the forward bias of 1.6 eV.

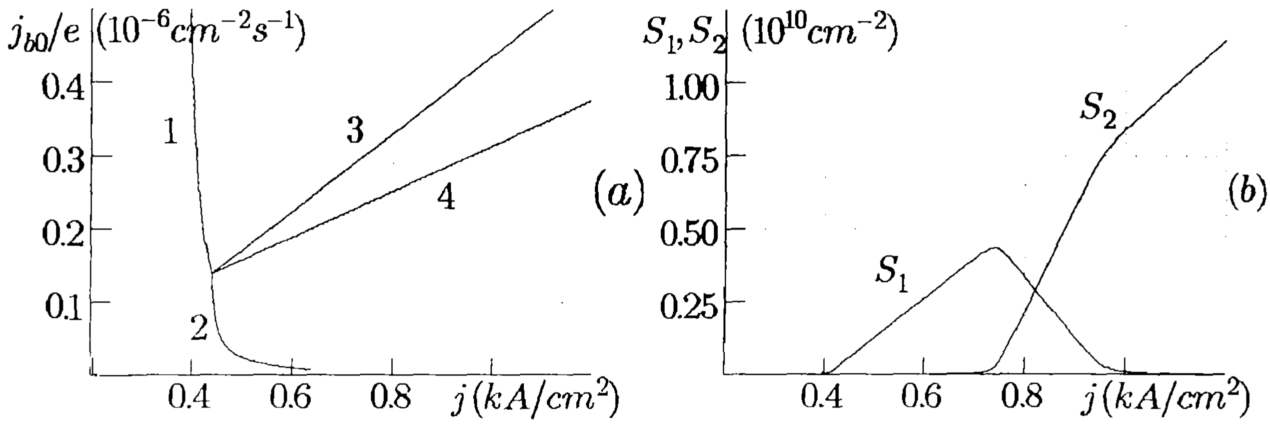

Figure 2: (a) Boundaries of the laser regimes: (1) the threshold for the λ_1 radiation; (2) the threshold for the λ_2 radiation; (3) the threshold for the λ_2 mode when the λ_1 mode lasing; (4) suppression of the λ_1 lasing in the presence of the λ_2 radiation. (b) Dependencies of the stationary photon densities S_1 and S_2 in the λ_1 and λ_2 laser modes on the pump current density j at $j_{b0}/e = 0.3 \times 10^{-6}cm^{-2}s^{-1}$.

Estimations performed with regard to Eq.(4) give for j_{b0}/e values of the order of $0.3 \times 10^{-6}cm^{-2}s^{-1}$ and, correspondingly, the mobility of electrons in the barrier region μ_e should be equal to $670cm^2/Vs$. The values found correspond to the experimental conditions. It follows from Fig.2 that shows boundaries of existence of different lasing regimes of the structure. In the calculation the experimental quantities of lasing wavelengths $\lambda_1 = 831nm$ and $\lambda_2 = 818nm$ were used. The loss was assumed to be equal $45cm^{-1}$.

If j_{b0} is large, electrons are free to pass from QW 2 into QW 1. Nonuniform excitation is practically absent and laser action begins at the longer wavelength λ_1. If j_{b0} is small, then charge carriers, on the contrary, are accumulated in QW 2 and lasing is occurred at the shorter wavelength λ_2. In the experiment according to our model estimations the parameter j_{b0} slightly exceeds the value at which the threshold currents for radiation at λ_1 (curve 1) and λ_2 (curve 2) coincide. With increasing the pump current laser action begins at the longer wavelength λ_1 and the population in QW 1 is fixed at the threshold level. The population in QW 2 continues to grow until lasing at the shorter wavelength λ_2 begins (curve 3). In this case, the injection in QW 1 is fixed. Since the λ_2 radiation is amplified in QW 1, the growth of the λ_2 mode power must be accompanied by a decrease in the λ_1 mode power up to the quenching of the latter (curve 4). Fig.2 (b) gives the stationary photon densities S_1 and S_2 of the laser modes at λ_1 and λ_2 depending on the pump current density j at calculated j_{b0}. It is in qualitative agreement with the experimental data.

4 Modified QW Laser Structures

Consider an asymmetric heterostructure when the radiation at a smaller wavelength emitted in one QW is absorbed in another QW. This situation is possible at a sufficiently large difference in lasing wavelengths. For the laser structure in hand, active layers 1 and 2 have the same composition $x = 0$, but differ in thicknesses ($d_1 = 12nm$, $d_2 = 4.4nm$). The conditions at which the laser operates at two wavelengths can be met by using a

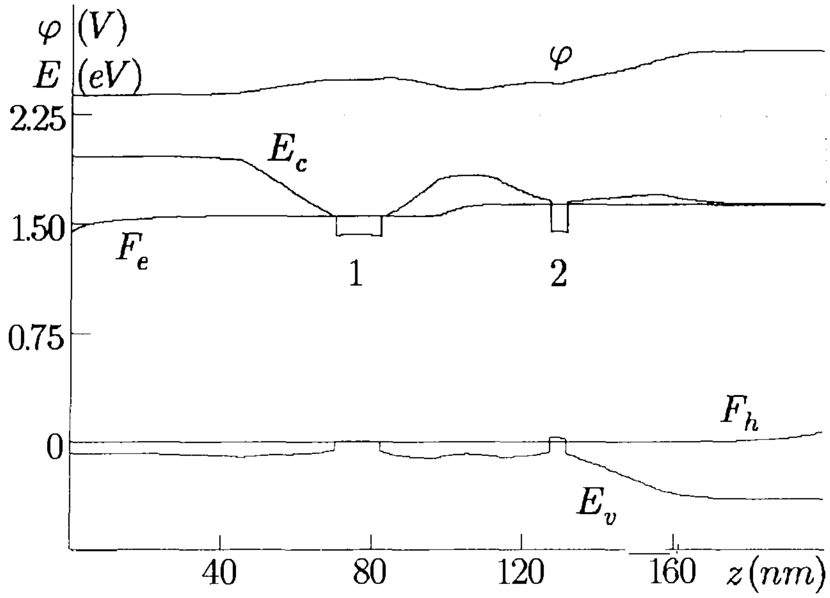

Figure 3: Band diagram of the QW laser under the forward bias of 1.64 eV.

barrier material with $x_b = 0.42$. One can also control the degree of nonuniform excitation of the QWs by varying the barrier width and its doping level. In addition, the potential barrier between the QWs contains two regions with a linear law of change in x (Fig.3).

Different regions of operation of an asymmetric QW heterostructure laser at a slow, quasistatic, increase in the pump current are illustrated in Fig.4. In region I the laser operates at the stable λ_1 mode. If the threshold at the wavelength λ_1 is not reached, the laser emits regular pulses at the wavelength λ_2 (region II). Simultaneous lasing at two modes occurs in regions III and IV.

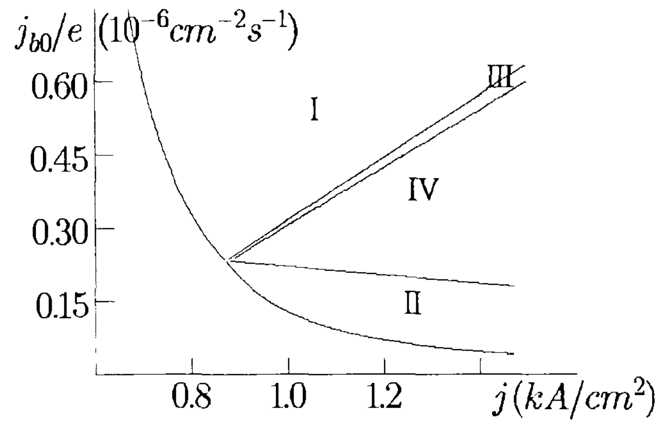

Figure 4: Regions of existence of the different regimes in the QW laser depending on the pump current j and parameter j_{b0}: (I) lasing at the single wavelength $\lambda_1 = 856nm$; (II) lasing at the single wavelength $\lambda_2 = 812nm$; (III) simultaneous stationary lasing at two modes; (IV) regular pulse generation at two laser modes.

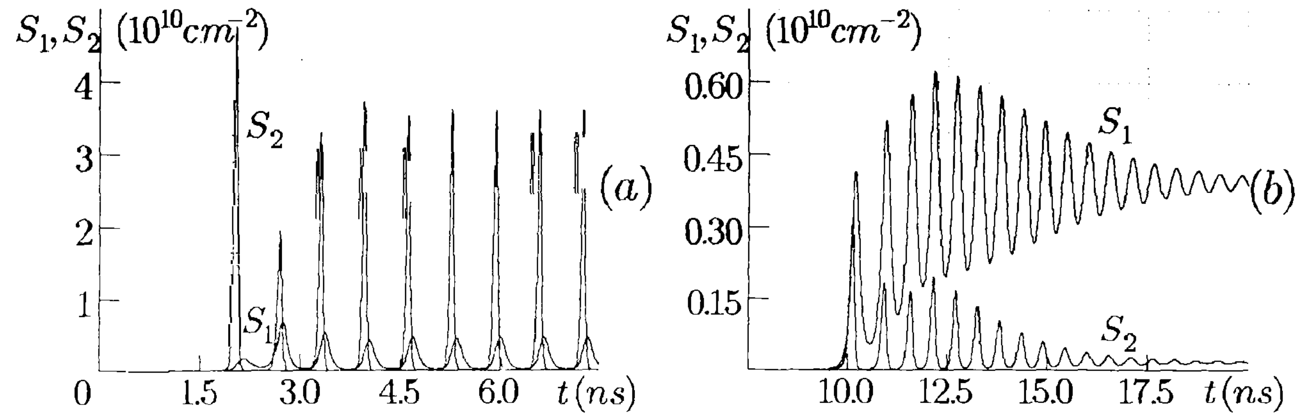

Figure 5: Dynamic output response of the QW laser at the pump current density $j = 1.1kA/cm^2$ and parameter $j_{b0} = 0.4 \times 10^{-6}cm^{-2}s^{-1}$: (a) stepwise current turning on; (b) turning on the pump current with the linear front duration of $12ns$.

Numerical calculations of laser regimes, where the front duration of current pulses is comparable with the carrier lifetime, show that unstable regions can be wider than according to the above used Lyapunov criterion (Fig.5). It is possible in the conditions of an abrupt current turning on because of a strong nonlinear dependence of the current j_{21} on the QW populations as it follows from Eq.(5).

5 Conclusion

For asymmetric QW heterostructure lasers, tunnelling and ballistic processes of carrier transfer between inhomogeneous excited QWs have been considered and mathematical modeling of the laser structures at forward bias has been performed. The calculations have been compared with experimental data. By choice of material compositions, doping and sizes of the QW and barrier layers it is possible to achieve different spectral and dynamic laser regimes.

6 Acknowledgements

Two of the authors (A.A.A.) and (V.K.K.) would like to thank the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste, where the work was completed during the Adriatico Research Conference on Ultrafast Phenomena and Applications and the Conference on Ultrafast Transmission Systems in Optical Fibres.

This work was supported by the Fund of Fundamental Investigations of the Republic of Belarus and granted in part by the Byelorussian Soros Foundation.

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