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Numerical analysis of an optoelectronic integrated device composed of coupled periodic MQW phototransistor and strained-QW laser diode

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Abstract

A rigorous numerical analysis for dynamic response of a voltage-tunable optoelectronic integrated device is presented. The device is composed of a coupled periodic multi quantum wells heterojunction phototransistor (CP-MQW HPT) integrated over a strained quantum well laser diode. The model is based on small signal analysis of device rate equations, for which we require to calculate laser diode gain and HPT electro-absorption coefficient. The Hamiltonian of quantum well laser diode structure is numerically solved by transfer matrix method taking in to account the strain effect and band mixing between heavy hole and light hole. The results are used to obtain laser diode gain. In order to calculate the electroabsorption coefficient, the exciton equation is solved numerically in momentum space using combination of the Transfer matrix method and Gaussian quadrature method. The valence band mixing is also considered here. The quantum confined Stark effect in the absorption spectra results in changes in the optical gain of the device which provides voltage tunability for the device. Based on the model, we show that the device has two operation modes: amplification for small optical feedback coefficient and switching for higher values.

Keywords: Optoelectronic integrated device; Strained quantum well; Coupled periodic multi quantum wells; Amplifier; Switch; Voltage-tunable

1. Introduction

A great interest has been focused on fabrication and analysis of the performance of optoelectronic integrated devices (OEID) for optical information processing [1–5]. Several functions such as optical amplification, optical switching and optical bistability can be obtained by vertical integration of a light detecting device and a laser diode.

Here to improve and enhance the performance of the device we propose a CP-MQW HPT integrated with strained quantum well laser diode (QW-LD). Using CP-MQW region between base and collector of HPT, is a way to improve the device performance and provides a large absorption peak change under a relatively low applied voltage. Superior performance such as extremely low threshold current density and high quantum efficiency has been demonstrated using strained QW-LD. A compressive strain lifts the heavy hole band edge and reduces its effective mass in the plane of the QW. So the density of state will be reduced and the LD achieves a smaller threshold current and a higher differential gain.

An accurate numerical model is developed to analyze the dynamic characteristics of the device taking into account the band mixing between heavy and light hole and strain effect for the first time. In this model the strained

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QW-LD gain and CP-MQW HPT electro-absorption coefficient are calculated to use in device rate equation analysis. First, the electron and hole subband energy levels and their envelope wave functions are calculated using transfer matrix method (TMM) considering finite barrier, the effect of strain and 4×4 Luttinger–Kohn Hamiltonian for valence band [6]. Then the optical matrix element for TE or TM polarization and Fermi levels are calculated to obtain the strained QW-LD gain. We add the effect of electric field to the model for CP-MQW HPT part to calculate the band structure under the stark Shift [7]. Next, the exciton equation in momentum space is solved numerically using the Gaussian quadrature method [8,9] to obtain exciton binding energy and oscillator strength. Then, the electro-absorption coefficient is calculated for different applied electric field for both TE and TM mode. The CP-MQW HPT optical conversion gain is obtained from the absorption spectrum [5]. The Stark shift of the excitonic peak in the absorption spectra results in optical gain of the device changes with applied voltage provides the voltage tunability performance. The dynamic response of QW-OEID is obtained based on the small signal analysis of the device rate equations. It is shown the device has two operation modes: amplification for small optical feedback coefficient and switching for higher values.

2. QW-OEID structure and operation

The schematic structure of the device is shown in Fig. 1. It is composed of CP-MQW HPT integrated over a strained QW-LD.

The strained QW-LD active layer consists of 10 $In_{1-x}Ga_xAs$ ($x = 0.42$) quantum wells of a thickness of 70 Å corresponding to an emission wavelength 1.51 μm under 0.36% biaxial compression and $In_{0.52}Al_{0.48}As$ barriers of 100 Å width. The cavity length is 300 μm. Strained QW-LD is preferred for its lower threshold current density and high quantum efficiency. The $In_{1-x}Ga_xAs/In_{0.52}Al_{0.48}As$ (lattice matched, $x = 0.47$) CP-MQW is used in the region between base and collector of HPT. Two different structures are considered for CP-MQW. One is a 23 coupled double quantum wells (CDQW) includes two 55 Å $In_{0.53}Ga_{0.47}As$ wells and 10 Å $In_{0.52}Al_{0.48}As$ barrier.

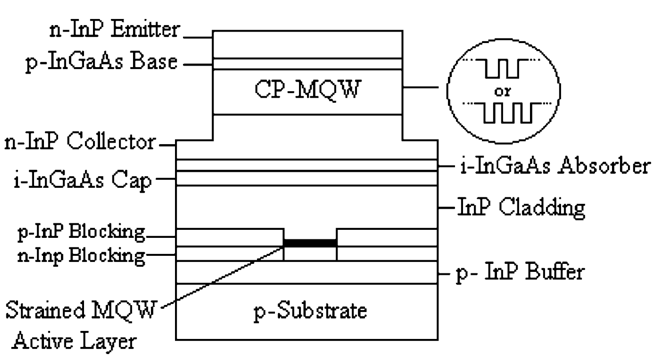

Fig. 1. Schematic structure of the QW-OEID.

Another is 23 coupled triple quantum wells (CTQW) consists of a 36 Å central well and two 39 Å end wells. These wells are separated by 3 Å thick $In_{0.52}Al_{0.48}As$ barriers. Each CDQW or CTQW is separated from another by 90 Å thick $In_{0.52}Al_{0.48}As$ barriers.

It is assumed that the OEID is already biased and the current inside the device is greater than the threshold current of strained QW-LD. Irradiating the device by a modulated optical signal leads to generation an amplified electrical signal in CP-MQW HPT. The photo generated current flows through the lower part and in the output an intensified optical signal is emitted. In this process some part of the emitted light is fed back transversely through the upper layers to CP-MQW HPT as a positive internal optical feedback. The amount of this feedback depends on several parameters such as the thickness and the material of the upper layers and geometrical structure of the device. The optical feedback plays an important role in realizing various optical functions such as light amplification and optical switching.

3. Theory of the analysis

To analyze the dynamic response of the QW-OEID the rate equation for electron density, $N(t)$, and photon density, $S(t)$, in the laser diode are used as following:

$$\partial N(t)/\partial t = I(t)/qV - N(t)/\tau_n - \upsilon_g g(N)S(t) \quad (1)$$

$$\partial S(t)/\partial t = \Gamma \upsilon_g g(N)S(t) - S(t)/\tau_p + \beta N(t)/\tau_n \quad (2)$$

$I(t)$ is the photo generated current of HPT due to the input optical signal and internal optical feedback, which drives laser part, is given by

$$I(t) = I_b + qGP_{in}/(h\nu_i) + ek_f GS(t)\alpha_m \upsilon_g V \quad (3)$$

where e is the electron charge, V the volume of active region, τ_n the carrier lifetime, υ_g the group velocity of light, $g(N)$ the quantum well optical gain, Γ the optical confinement, τ_p the photon lifetime, β the spontaneous emission coefficient, I_b the bias current, G the optical to current conversion gain of HPT, P_{in} the optical input power, ν_i the input optical frequency, k_f the internal optical feedback coefficient, and α_m the optical loss in active layer, respectively.

To obtain the dynamic response of the device, the input light is assumed to be a step function in time and the Laplace transform of Eqs. (1)–(3) is used. To do this, the strained quantum well laser diode gain, the CP-MQW exciton electro-absorption coefficient and the CP-MQW HPT optical conversion gain [5] are calculated.

3.1. Strained laser diode gain

The first step is the calculation of carrier density dependence of the laser diode gain. The local gain of QW structure including broadening effects is defined as [10]