STRAIN T-SHAPED QUANTUM WIRES: A PROPOSAL FOR ROOM TEMPERATURE OPERATING LASER

D.V. REGELMAN AND D. GERSHONI

The Physics Department , Technion- Israel Institute of Technology, Haifa, 32000, Israel E-mail: dany@ssrc.technion.ac.il

We propose a heterostructure laser based on a quantum wire of nanometer cross section embedded in its active region. The laser will be fabricated by the cleaved edge overgrowth technique by which uniform intersecting planes of strained GaAs thin layers, within an AlGaAs crystal will be formed. Our calculations show confining energies for both electrons and holes which are significantly higher than the thermal energy at room temperature. Thus, the proposed device is likely to operate well at room temperature and to materialize the predicted advantages of such a restricted geometry. We propose also a compatible novel two-dimensional structure which separate carriers and light confinement in two dimensions. The spectral gain and threshold current of the proposed device is realistically calculated. It is shown that these devices are best fitted into the active region of a surface emitting device.

1 Introduction

In an attempt to gain further from the reduction of dimensionality, a world wide research effort to bring 1D quantum structures such as quantum wires (QWRs) and 0D quantum structures such as quantum dots to the same degree of perfection achieved in the 2D quantum systems has been underway during the last two decades. So far, however, the effects of the reduced dimensionality were rather marginal, and the expected superior characteristics of lower dimensionality lasers, such as narrower gain spectrum, lower threshold currents, and lower temperature dependence, have yet to be demonstrated.

Among the most promising ways to achieve the goal of fabricating a lower dimensionality lasing device is cleaved edge overgrowth (CEO).[1] This technique utilizes two orthogonal directions of epitaxial growth, and thus, exploits the precision of layer thickness control to form uniform intersecting planes of semiconductor.

We propose here to use strained layer QWRs in which confinement to 1D is produced by one dimensional pseudomorphic strain[2]. The strain is induced in the (110) oriented cleaved edge QW by a (100) oriented strained layer QW. The lateral dimensions of these T-shaped strained QWRs (STQWRs) thus fabricated are comparable to the dimensions of the intersecting QW layers from which they are formed. Moreover, the two orthogonal epitaxial growth stages required for the fabrication of the wires can be used also for the creation of a one dimensional p-n junction[3] which supplies means of electrical injection selectively into the QWRs active region only[4].

It is clear, that in order to make these devices applicable, the energy associated with the lateral confinement has to be largely enhanced. We show here by the use of a theoretical model that this can be readily achieved by the combined effect of strain and geometry in a novel (STQWR) CEO heterostructure.

2 The proposed device

In Fig.1 we schematically describe the proposed CEO heterostructure. The structure consists of (001) oriented periodic structure of alternating 100Å and 300Å thick layers of $In_{0.2}Al_{0.8}As$ and $Al_{0.35}Ga_{0.65}As$ respectively. This strained layer superlattice (SLS) which is formed at the first stage of the epitaxial growth is then cleaved in situ to expose a (110) oriented facet onto which a 100Å thick layer of GaAs followed by a 400Å thick cap layer of AlGaAs is deposited during the second stage of the growth. Lattice mismatch of about 1.5% between the InAlAs layers and the GaAs substrate affect both growth stages. In our assessment of the strain tensor we assume that the growth is pseudomorphic at both the first and the second stage so that each epitaxial layer commensurates with the layer beneath it.

Our model calculations proceed along the lines described in Ref. 5. We use eight-band **k·p** Kane-Luttinger Hamiltonian with bulk parameters for each material region. The effect of the strain is included by the use of a phenomenological deformation potential theory with bulk deformation potentials. We use a Fourier expansion method to convert the eight coupled differential equations into a matrix eigenvalue problem which is then solved numerically. The resulting electronic and hole wavefunctions are shown in Figure 1. A similar procedure is used for calculating the 2D confined optical mode of this structure using the discontinuities in the index of refraction (at the wire optical transition wavelength) between the various semiconductor compound layers. The resulted shape of the optical field, optimized to maximize the overlap with the quantum wire confined carriers is displayed in Fig. 1. In order to check our model we compared between its results and published relevant data. The comparison is made in Fig. 2 where excellent agreement is obtained for CEO structures with no InAs in the CEO layers. The agreement with data obtained from CEO with InAs is less impressive, probably due to our too simple description of the strain fields. The calculated linearly polarized absorption spectra of one STQWR and a comparable CEO QW are presented in Fig. 3. The absorption is strongly polarized along the wire direction in agreement with the relevant experiment[2]. The confinement energy of carriers within the STQWR is ~150 meV as can be deduced from the shift towards lower energy of the absorption edge of the STQWR compared with that of the overgrown QW.

The calculated maximum spectral gain vs. carrier density for both structures are presented in Fig. 4.

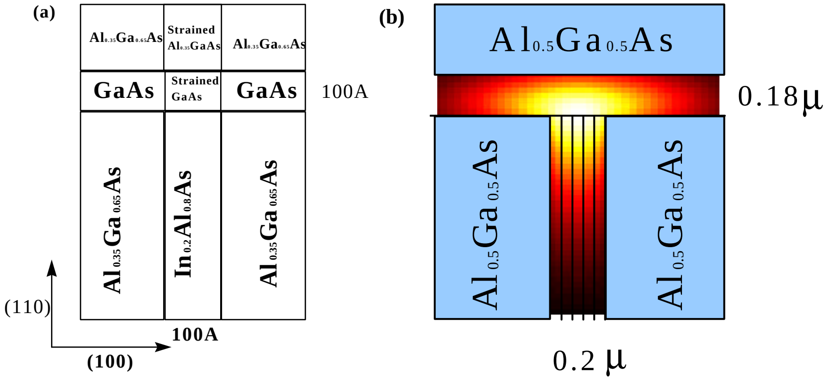

Fig 1: Schematic description of a single STQWR (a) The optimized laser structure with its 2D confined optical mode is shown in (b).

Enhancement of the optical field and electronic mode overlap (modal gain) is yet another advantage of the CEO technique.

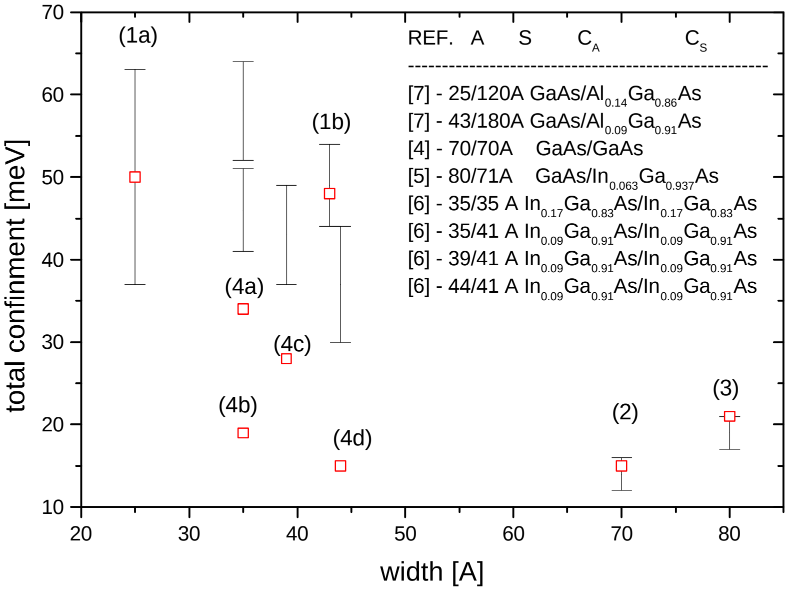

Fig. 2: Comparison between our calculations and CEO wire reported in the literature. The error bars represent structural uncertainties of 1 monoayer and composition uncertainties of 1%. A(S) stands for the (110)((001)) QW width, and c_A (c_S) for its composition.

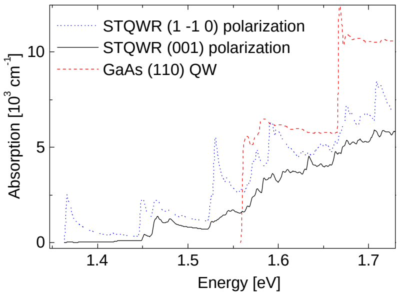

Fig 3: Calculated STQWR absorption spectra for light polarized normal and parallel to the wire.

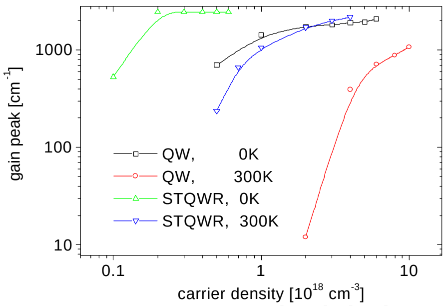

Fig 4: Maximum in the calculated spectral gain vs. carrier density for a single QW and a single STQWR at low and at room temperatures

2D light confinement can be also achieved by a careful design of a separate confinement structure as exemplified in Fig 1(b). The active region is embedded in a T-shaped structure of GaAs/$Al_{0.5}Ga_{0.5}As$ layers. The maximal electronic and optical mode overlap obtained this way amounts to 0.5%. Thus an optimal active region includes 9 STQWRs. For such structure we realistically estimated the carrier density of a STQWR laser at threshold taking into consideration typical mirror and absorption losses. The calculated carrier density at room temperature threshold was found to be 3×10^{18} cm^{-3} at which the maximal spectral gain is ~2000 cm^{-1}. From the polarization selection rules we note that optimal use of a CEO QWR laser requires a surface emitting device.

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