Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 745-748 **S-A-8**

Invited

Quantum Wire and Box Lasers

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Abstract: We discuss lasing characteristics of quantum wire and box lasers, showing extremely low threshold current, enhanced modulation bandwidth, and narrow spectral linewidth. Effects of the size fluctuation and the nonlinear gain on lasing characteristics are also discussed. Moreover, to estimate band structure of the quantum wire, results of the tight binding analysis are indicated. Finally we discuss importance to control both electron wave mode and photon wave mode for future high performance lasers, which leads to the concept of *quantum microlaser.*

1. Introduction

Recent progress of direct write lithography technology combined with epitaxial growth technology for quantum well (QW) materials leads to possibility of realizing low-dimensional quantum wells, i. e., quantum well wire (QWW) and quantum well box (QWB) structures. Since the first proposal of use of QWW and QWB arrays as the active layer of a semiconductor lasers by Arakawa and Sakaki in 1982[1], theoretical studies have revealed that important lasing characteristics such as threshold current characteristics, modulation bandwidth, and spectral properties are significantly improved in QWW lasers and QWB lasers[2-4]. Recently, attempt to fabricate QWW structures as well as their lasing operations has been demonstrated by several groups[5-9].

The purpose of this paper is .to discuss lasing characteristics of quantum wire and box lasers, showing extremely low threshold current, enhanced modulation bandwidth, andnarrow spectral linewidth. Effects of both the size fluctuation and the nonlinear gain on lasing characteristics are also discussed. Moreover, to estimate band structure of the quantum wire, results of the tight binding analysis are indicated. Finally we discus importance to control both electron wave mode and optical wave mode for future high performance lasers, which leads to the concept of *quantum microlaser.*

2. Threshold Current, Modulation Bandwidth, and Spectral Properties

With reduction of dimensionality of electron-motion freedom in QW, QWW, and QWB structures, the density of states changes from a parabolic function to a step-like function, a reciprocal of square-root function, and a delta-function, respectively, having less broadened density of states. As a result, if higher subband energy levels in both conduction band and valence band are ignored, the electronic state of QWB structures is equivalent to that of two-level atomic systems. Therefore, the basic properties of the QWB lasers should coincide with those of gas lasers.

Our calculation indicates that an extremely low threshold current less than 1μA might be obtained. This value is much smaller compared to QW lasers in which the expected lowest threshold current is about 100 μA. This extremely low threshold current results from very narrow gain profile due to the peaked density of states. In this calculation, it is assumed that the QWB structure has GaAs cubic active layers of 50Å, sandwiched by AlGaAs barriers of 50Å. Since higher subbands effects is almost suppressed in QWB structures with 50Å, the lasing characteristics in this laser exhibits achievable limits. It is assumed that all carriers are injected into the active region, ignoring non-radiative effects such as the carrier leakage effect. It is also important to choose the number of quantum boxes correctly to minimize the threshold current considering both the gain fattening effect and nonlinear gain effect.

Modulation dynamics of the semiconductor lasers are very important for practical application to high speed optical communication systems. The important parameter for the modulation bandwidth is the relaxation resonant frequency f_r, which can be derived by conventional rate equations as follows:

$$f_r = (g' P_0 / t_p)^{1/2} \qquad (1)$$

where, P_0, t_p, and g' are the stationary photon density in the cavity, the photon life time, and the differential gain (i.e., $g' = \partial g / \partial n$, where n is the carrier density), respectively. Eq.(1) indicates that increase of g', or P_0, and decrease of t_p leads to enhancement of f_r. In the QWB laser, we can expect that g' is much enhanced compared to DH lasers since the gain profile is extremely narrow. Therefore, use of the QWB structure in the semiconductor lasers leads to ultra high speed modulation.

The calculated results for g' show two important features. The first one is that g' is enhanced in QWB lasers compared to QW lasers by a factor of ten in the region of lower quasi-Fermi energy level. The maximum value of g' in a QWB laser reaches over $7 \times 10^{-5} cm^3 s^{-1}$ .The second one is that g' is strongly depending on the quasi-Fermi energy levels. This dependence is more pronounced with the decrease of the dimensionality of electron motion freedom. Due to this fact, the wide modulation bandwidth can be achieved by increasing N, since the quasi-Fermi energy can be reduced by increasing N. As a result, the modulation bandwidth f_r of the QWB laser is about three times as high as that of the QW laser and six times as high as that of a DH laser.

The spectral linewidth of the semiconductor laser is enhanced by a factor of $(1+\alpha^2)$ compared to Schawlow-Townes linewidth $\Delta \nu_{ST}$, where α is the linewidth enhancement factor which is expressed by

$$\alpha = (d\chi_R / dn) / (d\chi_I / dn) \qquad (3)$$

χ_R and χ_I are the rea part and the imaginary part of the complex susceptibility, respectively. In a gas laser system α is almost zero since the photon energy E_0 at which α becomes zero is tuned to the photon energy E_{max} at which the gain is maximum. On the other hand, the E_0 is usually detuned from the E_{max} in the bulk quantum well lasers, which leads to the increase of a. In fact, the value of a has been measured in the range between 2.2 to 7 in DH lasers. However, in QWB lasers in which the electronic state is similar to that of the gas lasers. α is expected to become zero. This is a big advantage for not only laser devices but also optical modulator with low chirping effects.

3. Effects of Size Fluctuation on Lasing Properties

Fabrication of the QWW structures and QWB structures have recently reported by several groups. However, at present stage, these fabrication include still difficult problems to solve. The first is to fabricate fine structures with smaller dimensions. In addition, even if this problem is overcome, the size fluctuation problem is still existing. With the decrease of cubic dimensions, this factor becomes more important. The size fluctuation is equivalent to inhomogeneous broadening in the gain profile which reduces the high gain effects. In fact, the size fluctuation leads to the energy broadening of the quantizing level. The calculation result indicates that g' decreases drastically with the increase of the fluctutation: even 10% fluctuation leads to dramatical reduction of g' by a factor of five. These results demonstrate importance to fabricate uniform QWB structures.

4. Nonlinear Gain Effects

With the increase of optical power, the nonlinear gain effect becomes dominant, which results in degradation of the modulation dynamics as well as spectra characteristics. We predicted theoretically that in QW lasers this nonlinear gain effects is enhanced[10], which was also evidenced experimentally[11]. This is due to the fact that the inhomogeneous broadening property is suppressed with the quantum confinement of electrons. Therefore, it is expected that in the QWB lasers in which the inhomogeneous broadening effect is most suppressed the gain nonlinearity is most enhanced.

For simplicity of our discussion, the single mode lasing condition is considered here. Therefore, only symmetric nonlinear gain is taken into account. In this case, the nonlinear gain $g\ (E\ ,n,I_{in}\ )$ of the semiconductor lasers due to the light with the photon energy of E can be expressed as follows

$$g(E,n,Iin) = g_l(E,n) - e(E,n)I_{in} \tag{4}$$

where $g_l(E,n)$, n, and I_{in} are the nonlinear gain, carrier density, and the light intensity inside the cavity (W/cm^2), respectively. $\varepsilon(E,n)$ is the nonlinear coefficient which can be derived using density matrix formalism for the third order purtervation theory.

Since $\varepsilon(E,n)$ includes the density of states, the nonlinear gain should be strongly affected by the dimensionality of electron motion in the active layer. The calculation result of the saturation power density I_S shows that, I_S is decreased with the increase of the dimensionality of the quantum confinement, where the saturation power density is defined as the power density at which the gain is half of the linear gain. These results indicate that the nonlinear gain effects is enhanced in QWB lasers.

5 Band Structure

Theoretical analysis predicted that characteristics of semiconductor lasers are significantly improved with the quantum wires , assuming the same effective mass as that of the GaAs bulk material. However, for more exact discussions, influence of change in the band structures, including the effective mass and nonparabolicity of the dispersion curve, should be carefully considered.

Here, we apply the tight binding method to the analysis of the valence band structure of GaAs/AlAs quantum wires.

We analyzed the band structures of GaAs/AlAs quantum wires (40Å×40Å GaAs wires) which are parallel to the [110] direction. The results indicate two important features.

(A)The effective mass of the first uppermost valence band (VB1) corresponding to the heavy hole is $0.168m_0$ which is 65% of the effective mass of heavy holes in quantum wells ($0.258m_0$) and 37% of that in the GaAs bulk ($0.45m_0$). In contrast, the effective mass of the conduction band is 0.103m0 which is larger compared to the effective mass of electrons in GaAs bulk ($0.067m_0$).

(B) Both the nonparabolicities and the negative effective mass properties of the second uppermost valence band (VB2) are more enhanced compared to those of quantum wells. The effective mass of VB3 is also slightly negative. Moreover,VB2 approaches VB3 at zone-center and approaches VB1 a little away from zone-center.

Changes in the effective masses indicated in (A) lead to reduction of threshold current, because these changes improve asymmetric properties of the density of states between the conduction band and the valence band. On the other hand, change in VB2 and VB3 shown in (B) causes increase of the threshold current. Therefore, in order to clarify whether threshold current increases, numerical calculations are required. The calculation of the modal gain as a function of the injected current, predicts slight increase (20-30%) of threshold current compared to the value predicted by the conventional method at the same modal gain.

6. Quantum Micro Lasers

Recently microcavity lasers have been investigated from the view point of controlling spontaneous emission effect. In this type of lasers, the spontaneous emission can be suppressed or enhanced, which leads to reduction of the threshold current. At present stage, because of technological limitations, vertical cavity structures are mainly discussed experimentally. The ultimate structures are ,however, the three dimensional microcavity. In this cavity, the photon (optcal) mode is completely controlled, resulting in single lasing mode operations. On the other hand, in QWB structures, the electron wave is three-dimensionally confined and single mode of the electron wave is realized.

If these two concepts are combined, a new type of lasers in which both the electron wave and the photon wave is completely controlled will be generated. We will call this laser *quantum micro lasers*.

7. Conclusion

In summary, we have investigated lasing characteristics of GaAs/AlGaAs lasers having QWB structures theoretically. The results indicate threshold current and modulation dynamics are significantly improved by controlling the total number of QWBs carefully as well as QWB dimensions. In addition, effects of the size fluctuation and the nonlinear gain effects are also discussed. Finally we briefly mention a new concept of the quantum micro lasers.

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