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REDUCTION OF THE FIELD SPECTRAL LINEWIDTH IN A QUANTUM-BOX
SEMICONDUCTOR LASER AND ITS EXPERIMENTAL DEMONSTRATION USING A
QUANTUM WELL LASER IN A HIGH MAGNETIC FIELD

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We investigate properties of the field spectrum of semiconductor lasers with quantum well box effects. The analysis reveals a significant reduction of the spectrum linewidth due to the quantum well box effect. This prediction is successfully demonstrated experimentally by placing a quantum well laser in a high magnetic field, in which Lorentz force as well as the quantum well potential forms a quasi-zero-dimensional electronic system. Furthermore, changes in the spontaneous emission spectrum of TE mode and TM mode are observed with the increase of the magnetic field, which results from suppression of anisotropic properties of the quantum well structure.

Effects of reduced dimensionality of electron motion alter various properties of semiconductor lasers. In 1982, Arakawa and Sakaki proposed the concept of the quantum box laser as well as the quantum wire laser[1]. In an ideal quantum box structures, electrons and holes have highly localized wavefunctions and the state space in each box is discrete as opposed to the quasi continuum of the bulk. The contribution to gain from each ideal quantum box arises from a pair of two level systems. In this case, the overall active layer would much like a gas laser in which the quantum boxes are analogous to the atoms in the gas.

In this paper, we investigate the field spectrum properties in the quantum box laser theoretically, and demonstrate its reduction experimentally using a quantum well laser in a high magnetic fields, in which zero-dimensional electronic systems are formed by both Lorentz force and the quantum well potential effects[2-4]. Furthermore change in the spontaneous emission spectrum of TE mode and TM mode is also discussed.

The linewidth of a semiconductor laser is given by the expression[5]

$$\Delta\omega = \frac{\theta}{2P}(1 + \alpha^2), \quad (1)$$

where γ is the spontaneous emission rate into the lasing mode, P is the number of photons in the lasing mode, and α is the linewidth enhancement factor resulting from the strongly detuned gain spectrum. In an external-cavity semiconductor laser the decreased spatial overlap of the gain with the field decreases θ , and the increased modal volume increases P thereby reducing linewidth. There is an alternative way to reduce the linewidth. That is a modification of the electronic state through the use of quantum size effects in the active layer.

To understand why this should happen, consider the expression for α in terms of optical gain $g(n)$ and resonant refractive index $\mu(n)$

$$\alpha = \frac{\omega}{2\mu_0} \frac{\mu'}{g'}, \tag{2}$$

where ω is the lasing frequency, μ_0 is the nonresonant contribution to the refractive index, and $\mu'(g)$ is the derivative of the refractive index (gain) with respect to carrier density n . In a bulk active layer α is typically -5 , thereby causing a degradation of spectral purity by a factor of 26 times [see Eq.(1)]. That α is nonzero and large in semiconductor lasers results from μ' being significant. This happens for two reasons. First, the laser gain spectrum is highly detuned, causing a strong contribution to $\mu(n)$ by the carriers at the lasing frequency. Second, band filling causes the gain and refractive index spectra to shift in frequency when the carrier density is disturbed. For these reasons, in Eq.(2) μ' is sizable (and in turn so is α) and it gives a measure of differential changes in that result from detuning and band filling.

On the other hand, in an ideal quantum box laser the situation would be very different. In such a device the active layer would consist of an array of structures (the quantum box) having a characteristic size of 100 \AA (ideally of the same shape and size). Electrons and holes residing in these structures would have highly localized wave functions and the state space in each box would be discrete as opposed to the quasicontinuum of the bulk. In the ideal quantum box laser the contribution to gain from each box would arise from a pair of two level systems (one for each electron spin). The overall active layer would be very much like a gas laser in which the boxes are likened to the atoms in the gas. In addition to a number of other differences, α in this ideal case would be zero provided the emission line is symmetrical and that lasing occurs at the peak of the emission line. Fig. 1 shows a calculated result of a quantum box laser as a function of quantum dimensions L . This result indicates a significant reduction of α with the decrease of the each quantum box dimensions. Note that α is almost equal to zero for the quantum dimensions less than 70 \AA .

Many of the characteristics we ascribe to this ideal device seem unattainable at the present time. Problems stem from the technological difficulties involved in fabricating quantum boxes. A means of testing the ideas discussed above without actually fabricating quantum boxes

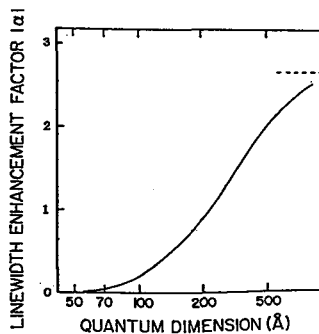


Fig.1 Calculated spectral linewidth plotted as a function of the the quantumbox dimensions

does exist, however. This is to apply high magnetic fields normal to the plane of a quantum well laser. By doing this we can achieve confinement of carriers in two directions via the Lorentz force and in the third direction from the quantum well carrier. Previously, we have employed this technique in bulk active layers to study quantum wire effects in semiconductor.[1,4]

In our experiment we used an Hitachi GaAs/AlGaAs multiple quantum well laser with self-aligned structure (five 3nm-thick GaAs quantum wells separated by 5nm-thick barrier layers). The room temperature threshold current was 42 mA and the lasing wavelength was 792.0 nm. Measurement results of the field spectrum for each magnetic fields are plotted as a function of inverse power in Fig.2. In this case there is an observable reduction of the linewidth as the magnetic field is increased. The reduction is as large as 2 function of inverse power for for a field strength of 19T. We believe this reduction is the result of emission from quantum box-like states in the active layer. The reduction is probably diluted by scattering effect. Another effect that could also weaken the observable reduction is the presence of other box states in the electrical proximity of the states which are responsible for lasing action. This would tend to detune the system and hence lead to field spectrum linewidth broadening as discussed earlier.

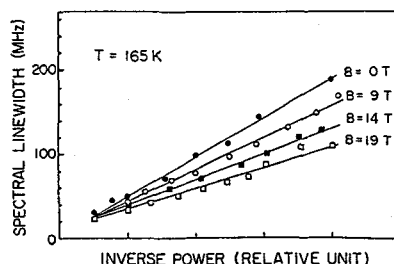


Fig.2 Measured spectral linewidth plotted as a function of inverse power for various magnetic fields

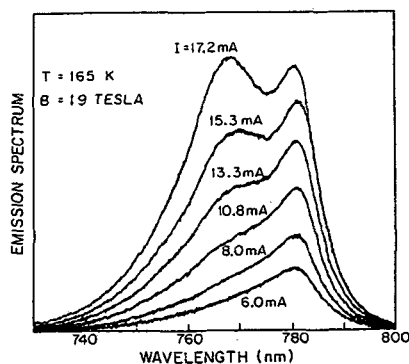


Fig.3 Observed spontaneous spectrum for various injected current at B=19T

The presence of other states was confirmed in measurements of luminescence which were performed on this device at 165 K. At low field strengths the luminescence had a single peak. At high field strengths, however, the spectrum had the dual peak structure shown in fig.3. This figure shows a sequence of spectra measured at a field strength of 19 T for different pump currents to the laser. In the spectra the low-energy peak is excited first. With increasing pump current the second peak is excited and eventually provides the gain necessary for lasing action in this device. As the field was reduced these peaks merged into one another, eventually becoming indistinguishable below 15T. The maximum separation of the peaks was 26 meV at 19T. Although it is possible that additional structure is hidden at these temperatures by scattering, we believe these peaks can be interpreted as transitions between Landau energy states in the conduction and valence bands of the quantum wells (i.e., simulated quantum boxes states).

Further confirmation for the quantum box effect is obtained in the spontaneous emission spectrum for TE mode and TM mode. Fig.4 (a)(b) show the spontaneous

emission spectrum for TE mode and TM mode respectively for various magnetic fields. Since the injected current is less than 1% of the threshold current, the stimulated emission effect can be ignored. For no magnetic field, TE mode spectrum has a peak at a wavelength corresponding to the heavy hole-electron transition, while TM mode spectrum has a peak at a wavelength corresponding to the light hole-electron transition. This result is well known to be due to the selection rule of the dipole matrix element. On the other hand, with the increase of the magnetic field, the spectrum configuration changes and the peak converge to the same wavelength for both modes. We believe that these changes result from suppression of anisotropic properties of the quantum well structure due to the high magnetic field.

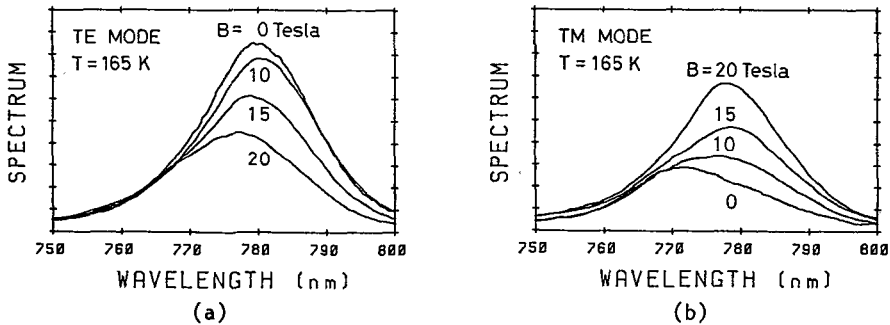


Fig.4 Spontaneous emission spectrum of TE and TM mode for various magnetic fields

In conclusion, we investigate properties of the field spectrum of semiconductor lasers with quantum well box effects. The analysis reveals a significant reduction of the spectrum line width due to the quantum well box effect. This prediction is successfully demonstrated experimentally by placing a quantum well laser in a high magnetic field, in which Lorenz force as well as the quantum well potential forms a quasi-zero-dimensional electronic system. Furthermore, change in the spontaneous emission spectrum of TE mode and TM mode is observed with the increase of the magnetic field, which results from suppression of anisotropic properties of the quantum well structure.

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