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Spontaneous Emission Characteristics of Quantum Well Lasers in Strong Magnetic Fields —An Approach to Quantum-Well-Box Light Source—

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Characteristics of a GaAs/AlGaAs quantum well (QW) laser diode are studied for the first time under strong magnetic fields up to 30 Tesla. When field normal to QW plane is increased, the spontaneous emission spectrum is found to shift toward the higher photon energy, following the shift $\hbar\omega_c/2$ of the lowest Landau level in the region of strong magnetic fields. Moreover, the emission spectrum is shown to be very little affected when magnetic fields are applied parallel to the QW plane. These results give evidence of light emission from a fully-quantized zero-dimensional carrier system in GaAs QW structures with strong magnetic fields normal to the QW plane.

The confinement of carriers in GaAs quantum wells (QW) has provided a number of unique features to the characteristics of QW lasers.[1,2] The reduction of the laser threshold current Jth[3,4] as well as its lasing wavelength controllability are typical examples. Such improvements are mainly due to the two-dimensional nature of carrier motions in QW potentials.[5] It has recently been suggested by the authors[6] that these improvements can be substantially enhanced if carriers are confined two or three-dimensionally by QW wires or QW boxes. As a first step toward QW box lasers, we study here the spontaneous emission characteristics of GaAs/AlGaAs QW lasers in strong magnetic fields up to 30 Tesla.

As is well known, carrier motions in QWs are quantized in the direction (//z) normal to the QW planes. If strong magnetic fields B are applied in parallel with the z-axis (B ⊥QW plane) as shown in Fig. 1, carrier motions in the QW active layers are quantized not only in z-direction but also in the two transverse directions (x, y). Hence, the application of magnetic fields to QW lasers quantizes the carrier motion completely, and results in the zero-dimensional carrier state. The energy levels of such electrons are completely discrete and given as

$$\varepsilon_{ln}=(l+1/2)\hbar\omega_c+\hbar^2(n+1)^2/2m_e^*(\pi/L_z^*)^2 \quad (1)$$

where $\hbar$ is Planck's constant divided by 2π, m_e^* is the effective mass of electrons, ω_c is the cyclotron angular frequency of electrons ($=eB/m_e^*$), L_z^* is the effective thickness of QWs and, l and n are quantum numbers. Corresponding expressions for holes can be obtained by replacing m_e^* with the effective mass m_h^* of holes. Note that the energy levels in actual situations have finite widths Γ_B for three different reasons: firstly, electrons are subject to scattering effects which disturb the completion of cyclotron motions; secondly, the system may have inhomogeneity; and, thirdly, the inter-well coupling of electrons in multiwell structures leads to the band formation. Equation (1) indicates that the effective energy gap E_g^* between the ground levels ($l=n=0$) of electrons and holes is given by

$$E_g^*=E_g+\frac{1}{2}\hbar eB(1/m_e^*+1/m_h^*)+\frac{\hbar^2}{2}(\pi/L_z^*)^2(1/m_e^*+1/m_h^*) \quad (2)$$

where E_g is the energy gap of GaAs.

In contrast, when magnetic fields are applied in parallel with the QW plane (B//x or y) the cyclotron motion of carriers is generally interrupted by the QW (as long as L_z^* is smaller than the cyclotron diameter). Hence, practically all the features of two-dimensional electron gas (2DEG) will be preserved. The effective energy gap E_g^* in this case is equal to that of the ordinary 2DEG except that some correction term is added due to the shrinkage of the wavefunction. We discuss this effect more in detail later.

Since the formation of the zero-dimensional carrier gas (0-DCG) in GaAs/AlGaAs quantum wells leads to the prescribed change in the effective energy gap (eq. (2)) and affects the form of the density of states, one should be able to demonstrate it by studying the light emission characteristics of QW lasers in the strong magnetic field. For this purpose, we have operated a multiquantum well (MQW) laser in the pulsed magnetic field and studied the spontaneous emission characteristics using the experimental setup of Fig. 2.

Pulsed magnetic fields up to 30 Tesla are generated by feeding a current from a 16 mF capacitor into a copper coil

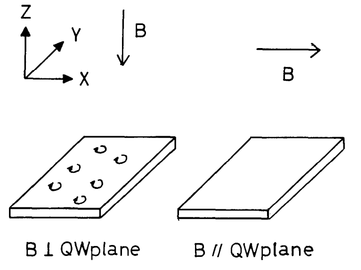

Fig. 1. Schematics of carrier motions in quantum well (QW) structures under strong magnetic fields B for two different field directions (a) QW plane ⊥ B, (b) QW plane //B.

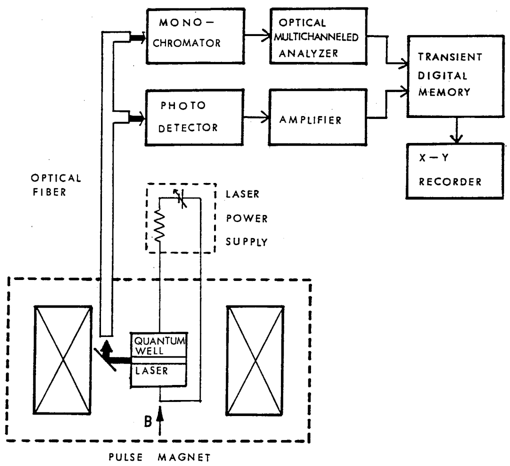

Fig. 2. A schematic drawing of the experimental setup.

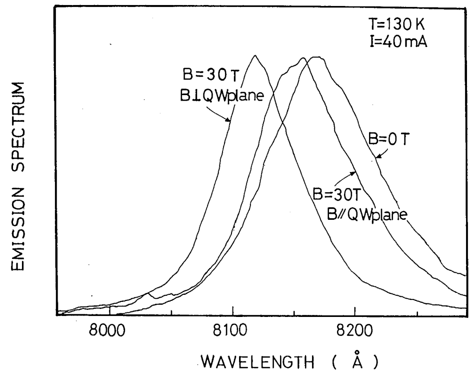

Fig. 3. Spontaneous emission spectra of a GaAs QW laser operated with and without magnetic fields $B=30$ Tesla. The field directions are perpendicular to or parallel with QW planes.

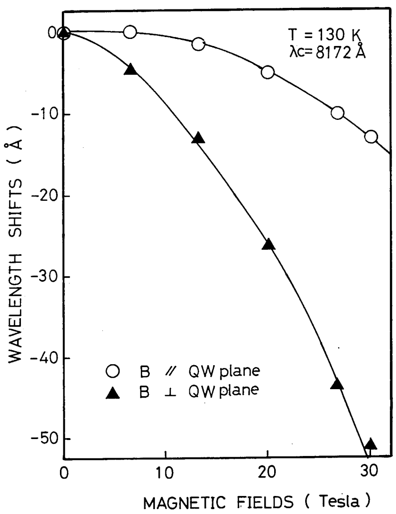

Fig. 4. The shift $\Delta\lambda$ of the peak in the spontaneous emission spectrum of QW lasers at 130 K plotted as a function of magnetic field B for the two different field directions. The wavelength λ_c of the peak without magnetic fields is 8172 Å.

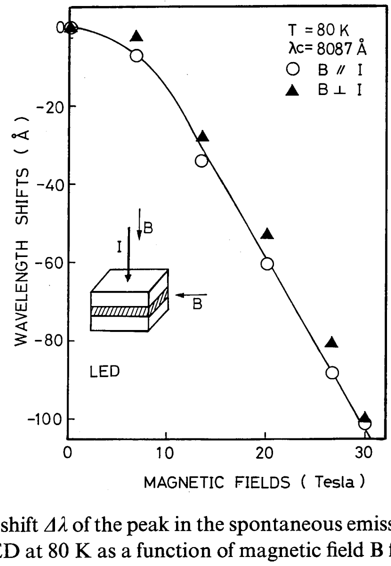

Fig. 5. The shift $\Delta\lambda$ of the peak in the spontaneous emission spectrum of a GaAs LED at 80 K as a function of magnetic field B for two different field directions. The wavelength λ_c of the peak without magnetic fields is 8087 Å. Note that the scale of the vertical axis is different from that of Fig. 4.

immersed in liquid nitrogen. The pulse has a waveform of the half-sinusoid $B_{max}\sin(\pi t/T)$ with the width T of about 10 msec. Lasers are operated for the time interval of 1 msec at the top of the pulse, where the magnetic field is almost constant. The light output from the laser is first reflected by a micro mirror and then transmitted through an optical fiber bundle to the outside of the cryostat. One part of the light output is fed to a 25 cm grating monochromator with 1200 lines/mm and its spectrum is detected by an optical multichanneled analyzer (OMA2 SYSTEM). The other portion of light output is fed directly to the photo-detector for the measurement of integrated intensity at the top of magnetic fields.

Multiquantum well (MQW) lasers used in this study are grown by molecular beam epitaxy on Si-doped GaAs(100) substrate at 760°C. Following the growth of a 0.42 μm n^+ GaAs buffer layer and 1.93 μm thick Sn-doped n^+-$Al_yGa_{1-y}As$ ($y=0.28$) cladding layer, the MQW active layer was formed, which consists of 16 layers of 100 Å-thick undoped GaAs quantum well separated by the 28 Å-thick undoped $Al_xGa_{1-x}As$ ($x=0.18$) barrier layers. Then, a 1.92 μm thick Be-doped p-$Al_yGa_{1-y}As$ cladding layer and an uppermost p^+ GaAs contact layer were grown. Using wafers thus grown, 10 μm-wide stripe-geometry lasers are fabricated with the cavity length of 200 μm by forming p-contacts with (Cr–Au) and n^+-contact with (Au–Ge–Ni). The threshold current is typically 150 mA at room temperature.

The spontaneous emission spectrum of MQW lasers was measured at 130 K with injected current 40 mA. Figure 3 shows the observed emission spectrum with and without the magnetic field B of 30 Tesla. Note that the spectral peak shifts clearly to the shorter wavelength by above 50 Å when the magnetic field is applied perpendicularly to QW planes (B ⊥QW). Contrastingly, the spectral peak is found to shift no more than 12 Å when B is applied parallel to QW planes (B//QW). To investigate the spectral peak shifts $\Delta\lambda$ in more shown in Fig. 4. One notices immediately that the peak shifts for the normal magnetic field (triangles) has much greater amount than those for the parallel magnetic field (circles), demonstrating clearly the anisotropy of QW potentials.

As for the magnitude of the shift $\Delta\lambda$ under the normal magnetic field, $\Delta\lambda$ in the range of low magnetic fields is far smaller than the shift of the ground Landau level $\hbar\omega_c/2$. This is due to the incompleteness of cyclotron motion ($\omega_c\tau \lesssim 1$). In the region of high magnetic fields, however, one notices in Fig. 4 that the incremental shift of spectrum $\Delta\lambda/\Delta B$ increases as B increases, and becomes as large as 3 Å/Tesla. This slope comes close to what is expected from the shift of the lowest Landau level. This indicates that carrier motions in quantum well planes are nearly quantized by the magnetic fields, and demonstrates the formation of the 0-DCG.

Another evidence of the formation of the O-DCG in QWs can be given by observing the anisotropy of the spontaneous emission spectrum with the magnetic field direction varied. Figure 4 shows clearly that the spectrum shift for the parallel field (B//QW plane) is very small up to 10 Tesla. This is because the cyclotron motion, whose diameter is 160 Å at 10 Tesla is interrupted by the quantum well potential, as discussed before. However, when B exceeds 15 T, the spontaneous emission spectrum shifts appreciably toward the shorter wavelength. This shift can be ascribed to the effect of an additional harmonic potential term $\alpha B_y(z-z_0)^2$, which appears in Hamiltonian in the presence of parallel magnetic field B_y.

Note that such a harmonic potential reduces the average extension of the carier wavefunction $\varphi(z)$ and results in the increase of energy eigenvalues of carriers. When the parallel magnetic field becomes extremely strong, this harmonic potential may well dominate the potential energy of Hamiltonian. In such a case, the carriers can complete the cyclotron motion within the well, since the cyclotron diameter becomes smaller than the thickness of the quantum well. The energy levels in such situations become entirelly identical with the usual Landau levels and the shift of emission spectrum is expected to be independent of the magnetic field directions. Note that the observation of this anisotropy is also evidence of the formation of the QW structure.

In order to further clarify the anisotropy of the spontaneous emission from a QW structure, we also measured, for comparison, emission characteristics of a GaAs light emitting diode, in which carriers are free to move in all three directions. Figure 5 shows the observed spectrum shift of the GaAs LED placed in magnetic fields of two different directions. One readily sees that the shift is almost independent of the field directions. Hence we can conclude that the observed anisotropy of spectrum shift in QW lasers is indeed evidence of anisotropic carrier states in QW structures. Note here also that the spectrum shift of the LED is almost identical with the predicted shift of the lowest Landau levels (eq. (2)) and proves the high quality of the LED active layer.

Lastly, a few remarks should be made on the full-width at half-maximum (FWHM) of the emission spectrum. Figure 3 shows that FWHM is reduced from 110 Å to 75 Å when the normal magnetic field is raised from zero to 30 Tesla. Such a reduction is most likely to result from the change of state density function from the original step-like form to the quasi-delta function form by the application of magnetic fields. Such an interpretation is supported by the fact that the reduction of FWHM under the parallel magnetic field is much smaller as shown in Fig. 3. Regarding this point, consideration should be given to the possible contribution of exciton states,[7,8] because the emission spectrum from exciton states is narrow even in the absence of magnetic fields. We think, however, that the contribution of exciton states is likely to be small in our experimental situations, since the QW laser was operated at medium current level.

In conclusion, we have demonstrated that the spontaneous emission spectrum of GaAs QW lasers shifts toward the shorter wavelength, when operated in high magnetic fields, with medium current level. The amount of such a shift and its marked dependence on magnetic field directions have given evidence of injection emission from fully quantized carrier states in semiconductors.

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References

1) J. P. van der Ziel, R. Dingle, R. C. Miller, W. Wiegmann and W. A. Nordland, Jr.: Appl. Phys. Lett. **26** (1975) 463.
2) N. Holonyak, Jr., R. M. Kolbas, R. D. Dupuis and P. D. Dapkus: IEEE J. Quantum Electron. **QE-16** (1980) 170.
3) W. T. Tsang: Appl. Phys. Lett. **39** (1981) 786.
4) R. Chin, N. Holonyak, Jr. and B. A. Vojak: Appl. Phys. Lett. **36** (1980) 19.
5) K. Hess, B. A. Vojak, N. Holonyak, Jr., R. Chin and P. O. Dapkus: Solid State Electron. **23** (1980) 517.
6) Y. Arakawa and H. Sakaki: Appl. Phys. Lett. **40** (1982) 939.
7) T. Ishibashi, S. Tarucha and H. Okamoto: *Proc. of International Symposium on Gallium Arsenide and Related Compounds 1981* (1982) 587.
8) C. Weisbuch, R. C. Miller, R. Dingle, A. C. Gossard and W. Wiegmann: Solid State Commun. **37** (1981) 219.