Extended Abstracts of the 15th Conference on Solid State Devices and Materials, Tokyo, 1983, pp. 51-55

B-1-1

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GaAs-AlGaAs Superlattice Grown by MBE

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MBE grown GaAs-$Al_xGa_{1-x}As$ superlattice structure is investigated from the view point of crystallography (X-ray diffraction and direct lattice-image observation by TEM), and optical properties (controllability of E_g, opposite Burstein shift, room-temperature exciton, and structure dependent refractive index). New device properties of an MQW laser diode/waveguide are described, which are an anisotropic optical gain, low absorption loss and stable longitudinal mode oscillation under high-speed modulation.

1. Introduction.

An attractiveness of superlattice is that the density-of-states function $\rho(E)$, the most important parameter to determine electronic and optical properties of semiconductor crystal, can be tailored by controlling the atomic arrangement of constituent elements. For any of the bulk crystals and their alloys, $\rho(E)$ is always parabolic with $\rho(E)=0$ at the band edge. In the contrast, for the superlattice structure, $\rho(E)$ is step-like with finite value even at the minimum energy. The step-like density-of-states makes the superlattice structure superior in optical properties to the bulk crystals, and a very low threshold laser diode has already been demonstrated by adopting a multi-quantum-well (MQW) structure in an active region of a DH laser diode[(1)]. This paper is a review of our recent studies on GaAs-AlGaAs superlattice structure grown by MBE. Crystallograghical studies are first presented, which include a direct lattice-image observation by TEM. Then, some of new optical properties of superlattice are described and followed by some novel device properties of MQW laser diodes.

2. Crystallograghical Studies.

(2-1) X-ray diffraction.[(2)]

An X-ray diffraction of a GaAs-AlAs superlattice grown on a GaAs substrate by MBE exhibits several small satellite peaks around a main reflection peak. The main reflection peak has its FWHM comparable with that of the substrate, showing good crystal quality as well as excellent uniformity in layer thicknesses in growth condition. Our finding that the main peak position (angle) gives accurately the AlAs content averagely included in the superlattice structure has led to a development of a non-destructive measurement method of L_z(potential well layer thickness) and L_B(barrier layer thickness).

(2-2) Surface morphology.[(3)]

The surface of GaAs-AlAs superlattice epilayer is mirror-like and much smoother than that of the mixed alloy $Al_xGa_{1-x}As$ films grown on the same condition by MBE.

(2-3) TEM observation.[(4)]

The coherency of layer thickness of GaAs-$Al_{.28}Ga_{.72}As$ superlattice in its growth direction was confirmed by TEM observation (Fig.1). This observation also confirmed that there is no alloy-clustering, which is a serious problem in MO-CVD grown superlattices.[(5)] A direct lattice arrangement observation was made by a high resolution TEM, which revealed that there is no lattice disorder across the hetero-interfaces.

(2-4) Low-temperature photoluminescence.[6]
77K photoluminescence half width of a GaAs-AlAs superlattice grown by MBE is so narrow that we can deny a possible fluctuation in well and barrier layer thicknesses of more than an atomic layer.

3. New Optical Properties of Superlattice.

(3-1) Opposite Burstein shift.[2]
Fig.2 shows the photoluminescence peak wavelength (energy) at 300K of GaAs-AlAs superlattices as a function of GaAs well layer thickness L_z. Undoped superlattices denoted by closed circles lie on a calculated curve very well. Superlattices doped by Sn uniformly to $2\text{-}5 \times 10^{18} cm^{-3}$ are denoted by open circles. For L_z greater than 50 Å, they deviate from the calculated curve toward higher energy side, just as in the case of a bulk GaAs crystal where this phenomenon is well known as the Burstein shift. On the other hand, superlattice with L_z smaller than 50 Å exhibits a deviation toward lower energy side. We call this an opposite Burstein shift. This shift may be related to the recent observation that the binding energy of a shallow impurity increases as decreasing the semiconductor film thickness.[7]

(3-2) Room-temperature exciton.[3]
Fig.3 shows optical absorption spectrum at 300 K of a GaAs-AlAs superlattice (solid line). At the energies of n=1,2,- - electron to heavy and light hole transitions (λ = 0.8 and 0.7 - - μm in this case), double peak structure appears. This structure does not change even at cryogenic temperature, where these peaks have been assigned as excitonic absorption.[8] The binding energy of exciton is known to increase in the two dimensional system where GaAs well layer thickness L_z is smaller than the excitonic Bohr radius.[9]

(3-3) L_B-dependent refractive index.[10]
Fig.4 shows refractive index spectra measured for four GaAs-AlAs superlattices with different values of L_z and L_B but with the same averaged Al content $\bar{x} = L_B/(L_z+L_B) = 0.55 \pm 0.03$. This measurement clearly demonstrates that the refractive index of superlattice is not determined solely by x, but it depends strongly on the barrier layer thickness L_B. A further measurement shows that the superlattice with L_B smaller than 45 Å has its dispersion curve similar to that of random alloy, and that the superlattice with L_B greater than 45 Å exhibits a dispersion curve intermediate between a bulk GaAs and a random alloy. This result shows that mutual coupling between adjacent potential wells determines the refractive index.
Another feature of superlattice is that the index at the effective bandgap energy, where a cusp appears as shown in this figure, differs in superlattices by as large as 0.2 to 0.3 from that in GaAs. This is in marked contrast to the random alloy $Al_xGa_{1-x}As$, where refractive index at its bandgap energy does not depend on x.

4. New Device Properties of MQW Laser.

(4-1) Polarization dependent optical gain.[11]
The MQW laser has in its active region a segment of superlattice (called a multi-quantum-well structure), which is anisotropic in structure. Consideration[12] both of the selection rule in the electron to hole recombination in this anisotropic structure and of the energy separation between the heavy hole and the light one in the MQW structure lead to an expectation that the optical gain for a TE polarized wave in the MQW waveguide is much larger than that for a TM polarized wave. The experimental result shown in Fig.5 exhibits that the gain for TE is larger by as much as 120 cm^{-1} at threshold than that for TM, whereas the difference in the conventional DH structure is at most 20 cm^{-1}. This large anisotropy in optical gain in MQW structure makes the MQW laser attractive as a polarization-stable optical source.

(4-2) Low-loss waveguide at its lasing wavelength.[13]
An MQW passive waveguide exhibits rather steep optical absorption spectrum as compared with the conventional DH waveguide. This reflects the step-like density-of-states of the two dimensional electrons and holes. An experimenatal result is shown in Fig.6. When both waveguide are current injected, spontaneous emission and lasing occur at wavelengths labeled by A and B, respectively. Althogh B is located in lower energy by 20-30 meV than A for both waveguides, it is important to note that the

optical absorption at the lasing wavelength B is much smaller in the MQW structure than in the conventional DH structure.

This means that the MQW waveguide is suitable for all optical integrated circuit including both active and passive waveguide elements on a wafer.

(4-3) Single longitudinal mode even under a high speed modulation.[14]

Due to the step-like density-of-states, the optical gain bandwidth of MQW structure is narrower , or 1/2-1/3 that of the conventional DH structure, so that the MQW laser is suitable for single longitudinal mode oscillation.

This was confirmed by comparing the spectral spreading under a high speed (500 Mbits/s) modulation to an MQW and a conventional lasers, both of which lased with a single longitudinal mode in their dc operation condition. The results are shown in Fig.7.

(4-4) Bandgap shrinkage rather than LO-phonon participation.[15]

As shown in Fig.6, laser oscillation occurs at lower energy than the spontaneous emission. Holonyak and his co-workers ascribed this lower energy shift to an LO-phonon participation.[16] But our studies on the emission peak shift due to injection current and on the observation of the spontaneous emission spectrum simultaneously with lasing do not find any LO-phonon contribution. Rather, this phenomenon can more easily be understood in terms of injected carrier induced effective bandgap shrinkage, as is also the case in the conventional DH laser.

5.Conclusion.

MBE grown GaAs-$Al_xGa_{1-x}As$ superlattice structure has been investigated crystallograghically and optically. Some new optical properties have been found. New device propertied have also been described on an MQW laser diode in comparison with the conventional DH laser. Demonstrated here are that the MBE is the finest epitaxial technology and that the superlattice is the most attractive in its optical properties as well as for optical device applications.

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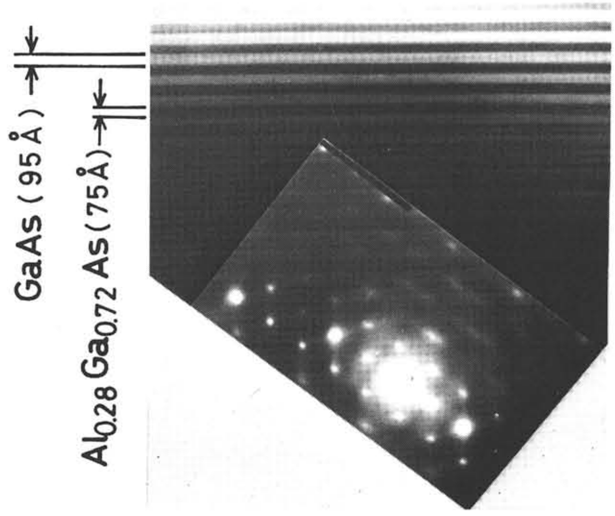

Fig.1 Cross-sectinal view of a GaAs-$Al_{.28}Ga_{.78}As$ superlattice observed by TEM. Inset shows diffraction spots.

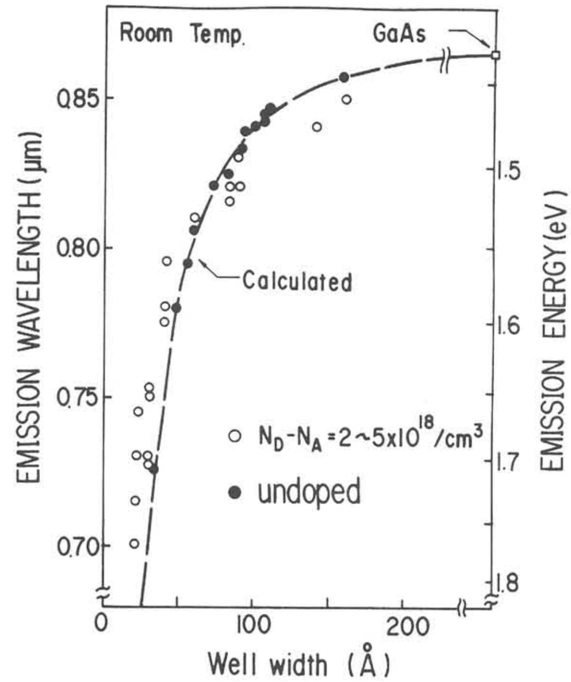

Fig.2. Photoluminescence wavelength (energy) as a function of L_z of GaAs-AlAs superlattice (300 K).

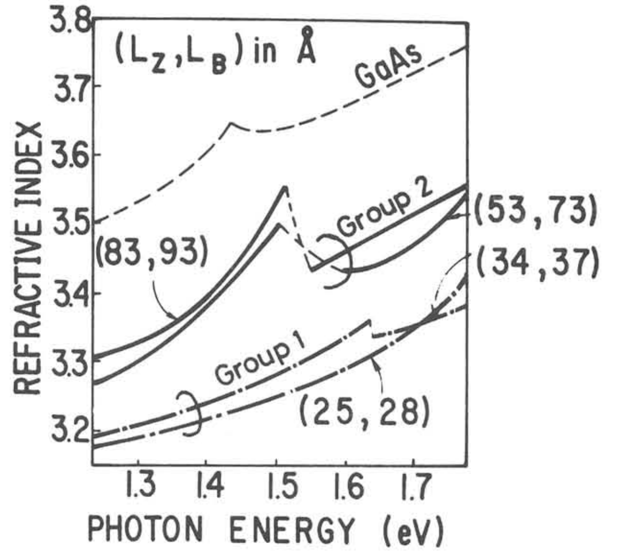

Fig.4. Refractive index spectrum for four GaAs-AlAs superlattice samples with different L_z and L_B but the same averaged AlAs content $x=L_B/(L_z+L_B)=0.55\pm0.03$.

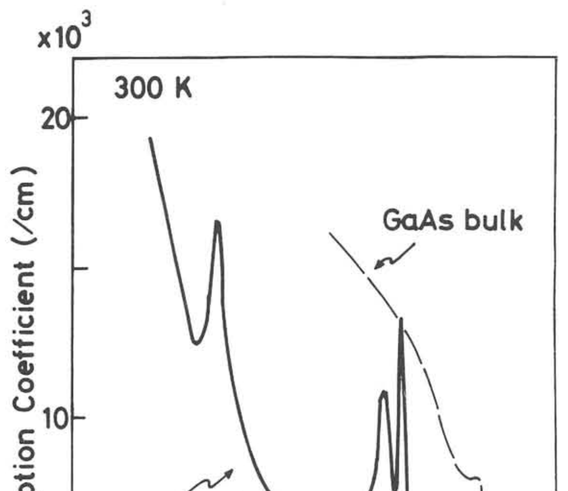

Fig.3. Optical absorption spectrum of GaAs-AlAs superlattice at 300 K.

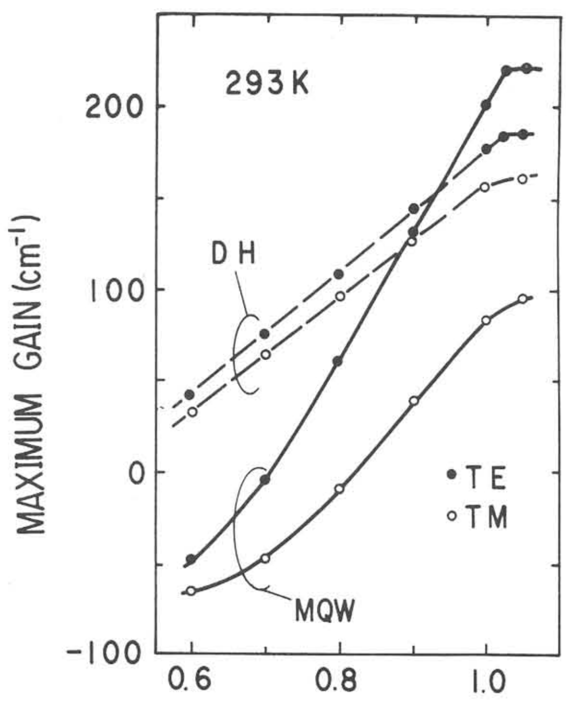

Fig.5. Optical gain for TE and TM waves as a function of injection current. Solid lines are MQW laser, and broken lines are conventional DH laser.

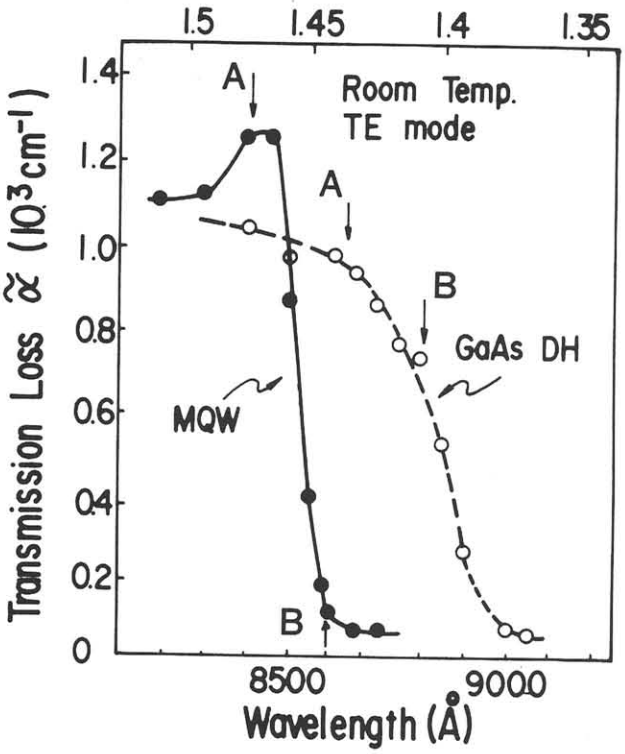

Fig.6. Optical transmission loss spectra for passive waveguides with MQW and conventional DH structure.
Arrows A and B denote the spontaneous and lasing wavelenghts, respectively, for each waveguide when current injected.

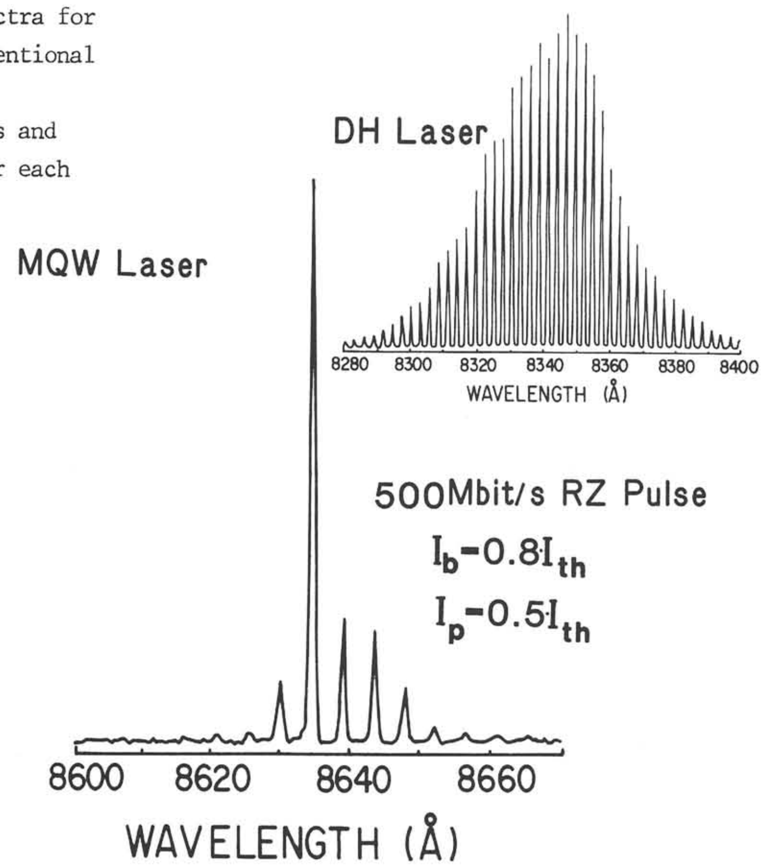

Fig.7. Comparison of oscillation spectrum between MQW and conventional DH laser modulated with the condition shown above, where I_b and I_p are bias and pulse current.