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Current injection GaAs-Al_xGa_{1-x}As multi-quantum-well heterostructure lasers prepared by molecular beam epitaxy

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Low-current-threshold room-temperature injection GaAs-Al_xGa_{1-x}As multi-quantum-well (MQW) lasers have been prepared by molecular beam epitaxy. Under pulsed current injection, lasing emission attributed to the $n = 1$ electron-to-light-hole ($1\ e$-lh) confined-particle transition was observed at threshold. Above threshold, lasing emission involving the $n = 1$ electron-to-heavy-hole transition ($1\ e - hh$) became dominant. Single longitudinal mode operation has also been observed for these broad-area MQW lasers. For heat-sink temperatures between 8 and 100°C, the lasing current threshold I_{th} for the $1\ e - hh$ transition has an exponential variation with temperature of the form $I_{th} \propto \exp(T/T_0)$, where $T_0 = 230$°K.

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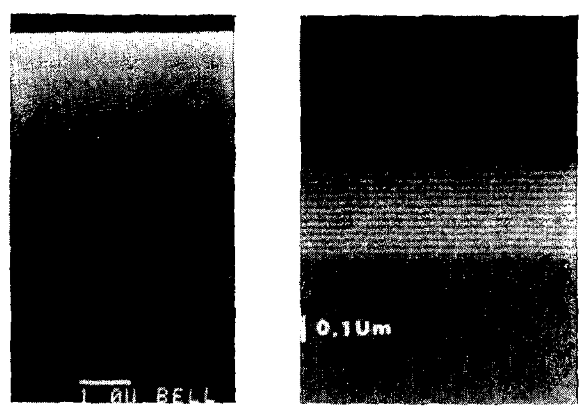
In this letter, we present results obtained from room-temperature pulsed ($\sim$500 ns, 100 Hz–1 KHz) current injection GaAs-Al_xGa_{1-x}As multi-quantum-well (MQW) heterostructure lasers[1-3] prepared by MBE.[4] This represents the first demonstration of current injection MBE GaAsAl_xGa_{1-x}As MQW lasers. Figures 1(a) and 1(b) show the SEM photographs of the cleaved cross-sectional view of the MQW laser structure at low and high magnifications, respectively. There are 14 GaAs quantum wells, each $\sim$136 Å thick, and 13 $Al_{0.27}Ga_{0.73}$As barriers, each $\sim$130 Å thick as calibrated by the growth time. The Al mole-fraction x of the two confinement Al_xGa_{1-x}As layers is 0.27. The above structure was grown under conditions similar to those employed for the growth of conventional low-curent-threshold DH laser wafers.[5,6] The multilayers were formed by operating the Al shutter manually. The flux distibution of the molecular beams resulted in a very slight thickness variation across the wafer.

For current threshold density evaluation,[5] broad-area lasers (375 μm long and 200 μm wide) having two saw-cut side walls and two cleaved mirrors were fabricated from the above wafer. The measured *averaged* pulsed room-temperature current threshold density J_{th} was 2 kA/cm^2. For comparison, we made an estimate of J_{th} for such MQW lasers using the J_{th}-d relation derived in Ref. 7. Since the averaged Al mole-fraction x of the multilayer (GaAs + $Al_{0.27}Ga_{0.73}$As layers) is 0.135, and the GaAs layers only occupy half of the total waveguide thickness, the actual optical confinement factor Γ for the above MQW laser is only $\sim$0.35. Using the optical absorption losses $\alpha_i = 10$ cm^{-1}, the internal quantum efficiency $\eta_{isp} = 1.0$, laser cavity length $l = 375\ \mu$m mirror reflectivity $R = 0.32$, and total GaAs layer thickness $d = 1900$ Å, the calculated J_{th} is 1.29 kA/cm^2. However, typical η_{isp} measured for saw-cut side wall broad-area DH lasers is only 0.6–0.8.[8,9] Thus, if $\eta_{isp} = 0.65$ is used, we obtain $J_{th} = 2.0$ kA/cm^2, which is the experimentally measured averaged J_{th}. Since η_{isp} includes the effects of interface recombination and bulk nonradiative recombination in various layers,[7] the value of 0.65 obtained for the MQW lasers confirms the very important conclusion that the MBE grown interfaces are essentially free of nonradiative defects. In spite of the fact that the number of interfaces has been increased from 2, as in DH lasers, to 28 in these MQW lasers, and that fact that the effect of interface recombination on J_{th} becomes increasingly serious as the active layer thickness decreases,[7] very low thresholds are obtained. It also confirms uneqivocally that the MBE grown Al_xGa_{1-x}As layers have low trapped densities, since there are 13 $Al_{0.27}Ga_{0.73}$As layers between the active GaAs wells.

To observe the confined-particle transitions in these MQW lasers, we studied their lasing spectral behaviors under pulsed current injection in the temperature range 8–110 °C and compared with a control DH laser also grown by MBE. The inset in Fig. 2(a) shows the typical lasing spectra near threshold of such a control DH laser (375 μm long, 200 μm wide, and 0.4 μm active layer thickness) at room temperature under pulsed operation. The peak of the lasing spectrum near threshold is at 8915 Å (1.3904 eV), which is about 34 meV below the energy gap of pure GaAs, $Eg = 1.424$ eV. The same result is obtained in GaAs-Al_xGa_{1-x}As injection lasers prepared by LPE.[8] This Stokes energy shift is believed to arise from stimulated emission involving band-to-impurity transitions. In the case of quantum well lasers, the impuri-



(a) (b)

FIG. 1. (a), (b) SEM photographs of the cleaved cross-sectional view of the MQW laser structure at low and high magnifications, respectively. The various layers from the top are: p^+-GaAs ($\sim 1 \times 10^{19}$ cm^{-3}), P-$Al_{0.27}Ga_{0.73}$As ($\sim 7 \times 10^{18}$ cm^{-3}), the unintentional doped multilayers of 14 GaAs wells and 13 $Al_{0.27}Ga_{0.73}$As barriers, and N-$Al_{0.27}Ga_{0.73}$As ($\sim 3 \times 10^{17}$ cm^{-3}).

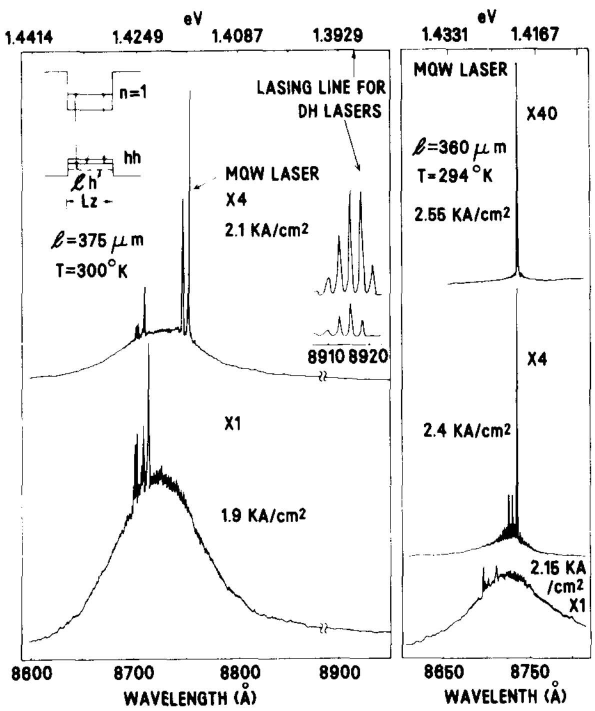


FIG. 2. (a) Lasing spectra for a MQW laser 375 μm long and 200 μm wide at two current injection levels. The inset shows the typical lasing spectra near threshold of a MBE grown conventional DH laser (375 μm long, 200 μm wide, and 0.4 μm active layer thickness) operated under similar conditions (b) Single-longitudinal operation of a broad-area MQW laser.

ty levels become associated with the individual quantum levels instead of the bulk band edge as in the case of bulk GaAs and are accordingly shifted to higher energies.

Figure 2(a) shows the lasing spectra obtained from MQW 375 μm long and 200 μm wide at two injection levels near threshold. At threshold, lasing occurs first on the high energy side of the spontaneous peak at $\sim$8708 Å (1.4234 eV), which is unusual and never observed in regular DH lasers. When compared with the lasing emission for a conventional DH laser, it is shifted to higher energy by $\sim$33.3 meV. However, with a slight increase in injection current, $I \lesssim 1.1\, I_{th}$, much stronger lasing lines occur at 8745–8751 Å (1.4174–1.4164 eV). The origin of this two-step behavior near threshold is very likely to result from the $n = 1$ electron-to-light-hole (1 e-lh, higher energy) and electron-to-heavy-hole (1-e-hh, lower energy) transitions. This energy level assignment is consistent with estimates of the $n = 1$ light- and heavy-hole splitting based on the known parameters of the structure and studies of the excitation spectra of the polarized multilayer luminescence generated with circularly polarized optical pumping. Above injection level of $\gtrsim 1.1\, I_{th}$, the 1 e-hh transition completely dominated the 1 e-lh transition. Lasing lines associated with transitions involving higher confined-electron levels were not observed under pulsed current injection in the temperature range 8–110 °C. The above behavior was common to all the MQW lasers examined. It is thought that by making the cavity length shorter, the resulting increased cavity loss will enable us to populate the higher n levels. However, it was found that even for lasers having cavity length as short as 70 μm, which has a cavity loss of 163 cm^{-1}, no lasing lines involving higher-order n transition was observed.

One tentative explanation for lasing to occur first at the 1 e-lh transition is as follows. As the electrons are injected from the N-$Al_{0.27}Ga_{0.73}As$ side across the multilayers and holes are injected from the P-$Al_{0.27}Ga_{0.73}As$ side in the opposite direction, the light holes which have higher mobility than the heavy holes arrive at those quantum wells close to the N side. In this region, the electron density in the wells is much higher than that in the wells near P side. Consequently, a population inversion between the electrons and light holes is achieved and stimulated emission occurs in these wells. As the injection level is increased, more electrons are injected into the wells across the entire multilayer towards the P side, where heavy holes are abundant. Eventually, a population inversion is achieved between the electrons and the heavy holes in all the wells and stimulated emission occurs via this process. Since the emission resulting from the 1 e-hh transition is TE polarized and of lower energy than that resulting from the 1 e-lh transition, it has a larger mirror reflectivity and less self-absorption loss. Furthermore, the TE polarized 1 e-lh transition has a larger oscillator strength than the TM polarized 1 e-lh transition. Once stimulated emission occurs via this process, it becomes the dominant process.

Lasing has also been observed with these MQW lasers at $\sim$10 and 300 °K by optical pumping. In all cases, *only* the lasing emission involving 1 e-hh transition was observed. This is consistent with and further supports the above explanation since with optical pumping no carrier transport is involved and electron-hole (heavy) pairs are generated uniformly acros the entire multilayer structure. As a result, the

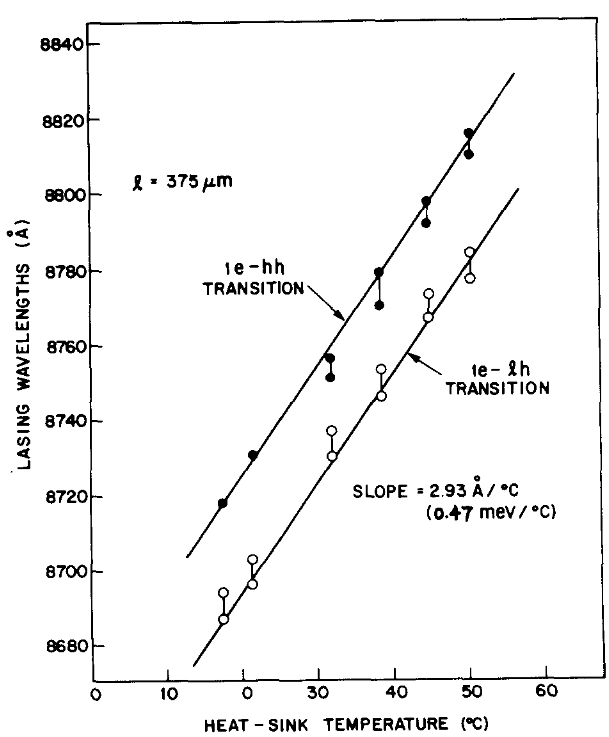


FIG. 3. Lasing spectral behavior of the 1 e-lh and 1 e-hh transitions for the same MQW laser given in Fig. 2(b) as a function of heat-sink temperature near the lasing threshold for the 1 e-hh transition. The solid and empty dots indicate the wavelengths of the dominant longitudinal modes for each confined-particle transition.

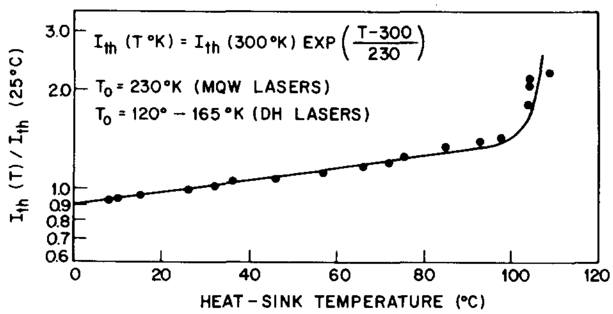


FIG. 4. The pulsed current threshold for the 1 e-hh transition as a function of heat-sink tempeature for a typical MQW laser.

light holes are less important for optical pumping. Emission involving higher n levels was not observed under optical pumping.

We also found that the MQW lasers tended to lase in fewer longitudinal modes. In fact, it is not unusual to observe single-longitudinal mode operation for current injection levels below certain levels, typically $\lesssim 1.3\ i_{th}$, and certain heat-sink temperatures. Such behavior is highly unusual for broad-area lasers. An example is shown in Fig. 2(b) [for comparison see the inset in Fig. 2(a) for a regular broad-area DH laser]. This result appears to be due to the narrowing of gain profiles in MQW lasers due to the density of states modification inherent in the thin GaAs wells.[10]

Figure 3 shows the spectral behavior of 1 e-hh and 1 e-lh lasing lines for the same MQW laser given in Fig. 2(b) as a function of heat-sink temperature near the lasing threshold for the 1 e-hh transitions remain nearly constant at ~ 6.3 meV. This indicates that the positions of the levels inside the well remain essentially constant with temperature. However, the absolute energies of these lasing lines decrease at a constant rate of 2.93 Å/ °C (0.47 meV/ °C) with increasing temperature. This corresponds to energy-gap shrinkage with increasing temperature. Such behavior is common to all the MQW lasers checked in this experiment. The double points for the same temperatures indicate that there are two dominant longitudinal modes operating at each 1 e-hh and 1 e-lh transitions.

The pulsed current threshold for the 1 e-hh transition was also studied as a function of heat-sink temperature T between 8 and 110 °C. A typical example is shown in Fig. 4. For $T \lesssim 100$ °C, one can approximate such behavior with the relation $J_{th} \propto \exp(T/T_0)$, where $T_0 = 230$ °K and T is in °K. Compared with regular DH lasers which have T_0 between 120 and 165 °K,[11] the J_{th} T behavior of MQW lasers represents a substantial improvement. The improvement in T_0 is believed to result from the density of states modification in MQW lasers.[10] This modification reduces the concentration of carriers near the Fermi tails, which are the carriers responsible for carrier leakage and hence increases J_{th} with increasing T.[12] The large increase in J_{th} beyond 100 °C is at present not fully understood.

In conclusion, low threshold GaAs-$Al_xGa_{1-x}As$ multi-quantum-well lasers have been prepared by MBE. This demonstrates conclusively that the MBE grown GaAs-$Al_xGa_{1-x}As$ interfaces and $Al_xGa_{1-x}As$ layers can be of very high quality. Under pulsed current injection, lasing emission involving 1 e-lh transition was observed at threshold. Above threshold, lasing emission involving 1 e-hh transition became dominant. Single longitudinal mode operation has also been observed in these broad-area MQW lasers. For heat-sink temperature between 8 and 100 °C, the lasing current threshold I_{th} for the 1 e-hh transition has an exponential variation with temperature of the form $I_{th} \propto \exp(T/T_0)$ where $T_0 = 230$ °K.

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