Double active region index-guided semiconductor laser

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A buried crescent InGaAsP/InP laser with a double active layer was fabricated. The laser showed very high characteristic temperature T_0 and highly nonlinear light versus current characteristics. A theoretical model using a rate equation approach showed good agreement with the experimental results.

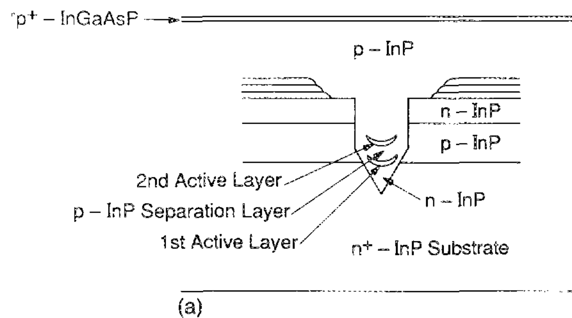
There has been continuous interest in making InGaAsP/InP lasers with a high characteristic temperature T_0.[1–5] A promising approach seems to be the double carrier confinement (DCC) structure.[4,5] In this structure a second "active" layer is grown to collect the carriers which leak out of the first active layer and to reuse them for radiative recombination. T_0 as high as 180 K has been reported.[4,5] However, the idea has only been demonstrated in broad-area (or wide stripe) lasers. It is thus of great interest to see if the idea is applicable to the commonly used laser structures, e.g., buried heterostructure (BH) or buried crescent (BC) lasers.

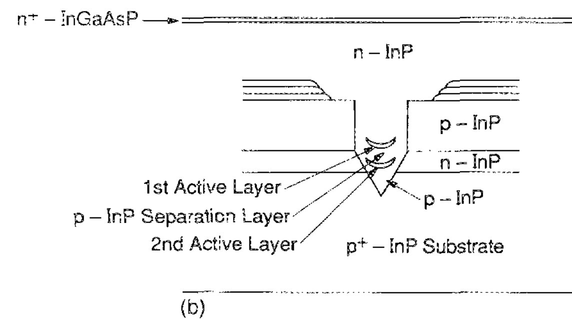
In this letter, we report on the first attempt to build a real index-guided laser with two active layers. In addition to the increase of characteristic temperature, we found highly nonlinear behavior in the light versus current (L-I) characteristics of the DCC laser. A theoretical model shows good agreement with the experimental data.

Buried crescent (BC) structures were used for our study. Lasers were made on both an n-InP substrate and p-InP substrate. A schematic structure of the laser is shown in Figs. 1(a) and 1(b). A scanning electron microscope (SEM) picture of the double active layer is shown in Fig. 1(c). The fabrication processes of the laser involve two-step liquid phase epitaxy (LPE) growth which has been described in great detail in the literature.[6] The only difference is the growth of two active layers by "three-melt technique."[5] In the whole second growth cycle only one InGaAsP melt is used for the growth of two active layers, which ensures the exact overlap of the transition gain profile of the two layers.

The threshold currents of the BC DCC lasers on n-InP substrate are in the range of 20–45 mA for a cavity length of $\sim 250\ \mu$m. Lasers made on the same wafer with a single active layer had a threshold current of $\sim$ 10–15 mA. For the BC DCC laser on the p-InP substrate, the threshold currents are 40–60 mA, while threshold currents of lasers made from the same solution with single active layers are typically 15–20 mA. The emitting wavelength of the BC DCC laser is $\sim 1.3\ \mu$m. For the wafers we processed, the thicknesss of the active layer is $\sim$0.15–0.25 μm, the separation between the two active layers is 0.05–0.35 μm, and the width of the active layer is 2–2.5 μm.

The main feature of the light output versus current characteristics (L-I curve) is the high nonlinearity. Figure 2 compares the cw L-I curves of a typical BC DCC laser and a single active layer BC laser. The L-I curve of the conventional BC laser shows good linearity while the BC DCC laser displays optical switching behavior. An optical power jump of 2–3 mW at the threshold for BC DCC lasers was observed. The external quantum efficiency in this region is





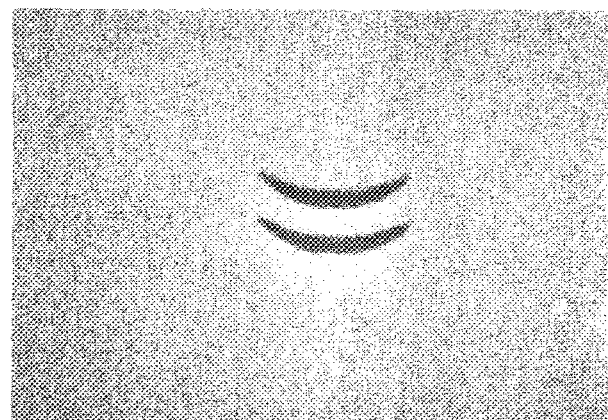


FIG. 1. (a) Schematic structure of BC DCC laser on n-InP substrate. (b) Schematic structure of BC DCC laser on p-InP substrate. (c) SEM picture of the double active region.

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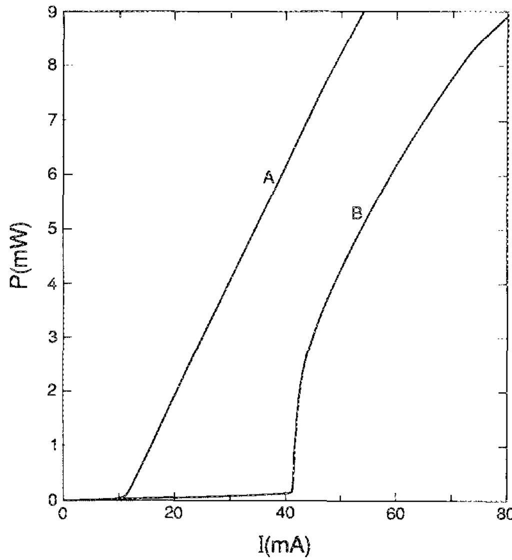

FIG. 2. Light vs current curves of BC lasers. (a) BC laser with single active layer. (b) BC DCC laser.

much higher than that of the single active layer BC laser, and it can be larger than 100% per facet. After the initial switch, there is a region in which the L-I curve of the BC DCC laser has comparable slope as that of the single active layer BC laser. Then the optical power gradually saturates. The power of the BC DCC laser saturates much faster than the conventional BC laser.

The temperature dependence of the threshold current of the BC laser was examined. Assuming $I_{th} \propto e^{T/T_0}$, the characteristic temperature T_0 for our single active layer BC lasers is typically 60 K. For the BC DCC laser on p-InP substrate, measured T_0 ranges from 120 to 250 K (Fig. 3), depending on the laser parameters (e.g., the thickness of the active layers and the separation between the two active layers). The measured T_0 for the BC DCC laser on the n-InP substrate is somewhat lower, but is still ~ 30 K higher than that of the single active layer BC laser. The possible reason is that the separation between the two active layers for the wafer we cessed is too small. Another possibility is the shift of the ction due to Zn diffusion during the growth.[5]

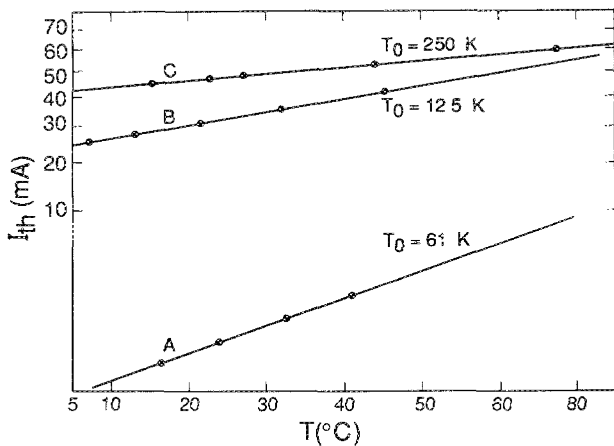

FIG. 3. I_{th} of BC lasers as a function of temperature, showing different T_0 values. (a) BC laser with single active layer. (b), (c) BC DCC laser on p-InP substrate.

For better understanding the BC DCC laser, an analysis using rate equations has been carried out. The equations which govern the carrier density N_i in the ith active layer and photon density P in the lasing mode are

$$\frac{dN_1}{dt} = \frac{J_1}{ed_1} - B(N_1 + N_{A1})N_1 - A(N_1 - N_{tr})P - R_{\text{Auger},1}, \quad (1)$$

$$\frac{dN_2}{dt} = \frac{J_2}{ed_2} - B(N_2 + N_{A2})N_2 - A(N_2 - N_{tr})P - R_{\text{Auger},2}, \quad (2)$$

$$\frac{dP}{dt} = A\left[\Gamma_1(N_1 - N_{tr}) + \Gamma_2(N_2 - N_{tr})\right]P - \frac{P}{\tau_p} + \beta B\left[\Gamma_1 N_1(N_1 + N_{A1}) + \Gamma_2 N_2(N_2 + N_{A2})\right], \quad (3)$$

$$J_{\text{Leak},1} = J_2 + J_{\text{Leak},2}, \quad (4)$$

where $R_{\text{Auger},i} = C\left[(N_i + N_{Ai})^2 N_i + (N_i + N_{Ai})N_i^2\right]$ (Ref. 7) is the Auger nonradiative recombination rate, J_i is the carrier recombination current in the ith active layer, B is the radiative recombination constant, N_{Ai} is the acceptor density in the ith active layer, A is the gain constant, N_{tr} is the transparency carrier density, d_i is the active layer thickness, Γ_i is the optical mode confinement factor of the ith active layer, τ_p is the photon lifetime, β is the coupling constant for spontaneous emission into the lasing mode, and $J_{\text{Leak},i}$ is the leakage current over the heterobarrier from ith active layer for which the model in Ref. 7 has been adopted.

Using reasonable parameter values, we solved Eqs. (1)–(4) numerically. We found that up to threshold the second active layer is absorbing. At threshold the photon density P increases. Also the carrier densities in the two active layers redistribute; a step increase in N_2 and a step decrease in N_1 occur. The second active layer is bleached almost to transparency. This accounts for the optical switching behavior of the BC DCC laser. It is interesting to notice that the feature of the L-I curves depends on the spontaneous emission factor β. For a real index-guided laser as a BC laser, β is small ($\sim 10^{-4}$). A jump in output power at threshold is present. However, for gain-guided structures as those in Refs. 4 and 5, β is much larger, e.g., (5×10^{-3}), which smears out any optical power jump as confirmed by our calculations. It was also found that the very large T_0 value cannot be attributed only to the carrier leakage. The Auger nonradiative recombination process in this double active layer configuration plays an important role. A detailed description of the calculated results will be published elsewhere.

In conclusion, a BC DCC laser was fabricated by a two-step LPE growth and a "three-melt technique." The laser showed high characteristic temperature T_0. Threshold current was typically 2–3 times higher than that of the single active layer device. An optical switching behavior was observed which may be of practical interest. A theoretical model using the rate equation approach showed good agreement with experimental results.

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