Lasers with asymmetric barrier layers: A promising type of injection lasers

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Abstract

We present an overview of our theoretical and experimental work on a novel type of semiconductor lasers – quantum well (QW) lasers with asymmetric barrier layers (ABLs). Our experimental work supports our theoretical derivations — ABL QW lasers demonstrate superior operating characteristics as compared to conventional QW lasers. In particular, the threshold current is lower and more temperature-stable, the light-current characteristic is more linear, and the wall-plug efficiency is higher in ABL lasers.

1. Introduction

Low lasing threshold, as well as temperature-stable and high-power operation, have always been desirable in semiconductor lasers [1]–[13]. In conventional diode lasers with a quantum-confined active region, a significant fraction of electrons and holes does not enter into the active region and thus does not contribute to stimulated recombination therein. Instead, this fraction is consumed by spontaneous recombination in the waveguide region [optical confinement layer (OCL)], wherein the carriers are initially injected from the cladding layers and which contains (in its central part) the active region [Figure 1(a)]. The parasitic electron-hole recombination outside a low-dimensional active region presents a major challenge in conventional injection lasers. Due to this recombination, the laser characteristics are adversely affected – the threshold current is increased and more temperature-sensitive and the light-current characteristic (LCC) is sublinear, even in the absence of heating effects.

To overcome the limitations placed on the operating characteristics by recombination outside the active region, novel designs of semiconductor lasers were proposed – one using double tunnelling-injection (injection of both electrons and holes) into the active region [14]–[22] and the other using asymmetric barrier layers (ABLs) [15]–[17] [one on each side of the active region – see Figure 1(b, c)]. The active region in these novel lasers can be in the form of either a single quantum well (QW) or a single layer with quantum dots.

Here we present an overview of our theoretical [23]–[27] and experimental [28]–[32] work on ABL QW lasers. Our experimental work supports our theoretical derivations — ABL QW lasers demonstrate superior operating characteristics as compared to conventional QW lasers. In particular, the threshold current is lower and more temperature-stable, the LCC is more linear, and the wall-plug efficiency is higher in ABL lasers.

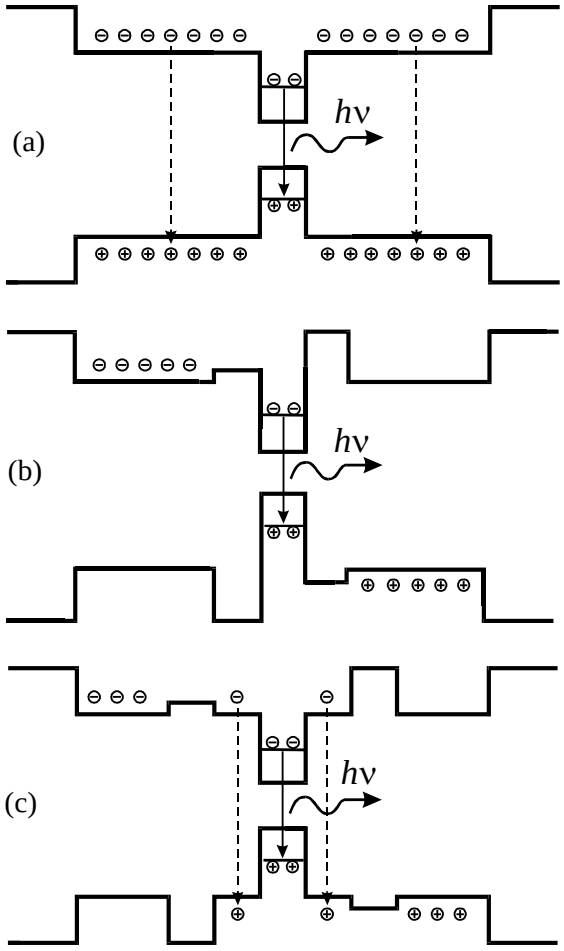

Figure 1. Schematic energy band diagrams of a conventional laser (a) and ABL lasers without (b) and with (c) intermediate layers. The vertical arrows show the electron-hole recombination.

2. ABL laser structures

Figures 1(b, c) show the schematic energy band diagrams of ABL lasers. The barrier layers are asymmetric in that they have considerably different heights for the carriers of opposite signs. The layer located on the electron- (hole-) injecting side of the structure [left- (right-) hand side in Figs. 1(b, c)] provides a low barrier (ideally no barrier) for electrons (holes) [so that it does not prevent electrons (holes) from easily approaching the active region] and a high barrier for holes (electrons) [so that holes (electrons) injected from the opposite side of the structure do not overcome it].

The use of ABLs in the structure of Figure 1(b) will thus secure that there will be no electrons and holes simultaneously (and hence no parasitic electron-hole recombination) outside the active region. In the structure of Figure 1(c), there will however be both electrons and holes (and hence some electron-hole recombination) not only in the active region but also in two intermediate layers located between the active region and each of the ABLs. The presence of these thin intermediate layers may be required in order to facilitate the flux switches during epitaxial growth process and to prevent from the active region re-evaporation [33, 34].

We discuss below the calculated and experimental characteristics of ABL QW lasers.

3. Threshold characteristics

The threshold current density of a QW laser is given as the sum of the current densities of spontaneous radiative recombination in and outside the QW,

$$j_{\text{th}} = j_{\text{spon}}^{\text{QW}} + j_{\text{spon,th}}^{\text{outside}} . \quad (1)$$

The current densities of spontaneous radiative recombination in and outside the QW are

$$j_{\text{spon}}^{\text{QW}} = eB_{\text{2D}} n^{\text{QW}} p^{\text{QW}} , \quad (2)$$

$$j_{\text{spon, th}}^{\text{outside}} = eb^{\text{outside}} B_{\text{3D}} n_{\text{th}}^{\text{outside}} p_{\text{th}}^{\text{outside}} , \quad (3)$$

where e is the electron charge, B_{2D} is the spontaneous radiative recombination coefficient for a two-dimensional region (QW) (see [35] for the expression for B_{2D}), n^{QW} and p^{QW} are the two-dimensional electron and hole densities in the QW, b^{outside} is the thickness of the region outside the QW wherein the parasitic electron-hole recombination occurs, B_{3D} is the spontaneous radiative recombination

coefficient for the material of that region (see [5, 35] for the expression for B_{3D}), and $n_{th}^{outside}$ and $p_{th}^{outside}$ are the free electron and hole densities in that region at the lasing threshold.

In conventional QW lasers (CQWLs), $b^{outside}$ is the thickness of the entire OCL and hence is large [300 nm in the structure of Figure 5(a)]. In the ABL QW laser with intermediate layers, $b^{outside}$ is the sum of the thicknesses of the intermediate layers, which are very thin [5 nm each in the structure of Figure 5(b)], and hence is very small. In the ABL QW laser without intermediate layers, $b^{outside}$ is simply zero since there is no region outside the QW wherein the electron-hole recombination occurs. Consequently, the parasitic recombination current density $j_{spon,th}^{outside}$ is high in CQWLs, low in the ABL QW laser with intermediate layers, and zero in the ABL QW laser without intermediate layers. This is illustrated in figures 2 and 3, which show the calculated threshold current density against cavity length and temperature, respectively. As seen from the figures, the threshold current density is considerably higher in the reference CQWL as compared to both ABL QW lasers and there is no much difference between the threshold current density in the ABL QW lasers without and with intermediate layers.

The temperature dependence of threshold current in semiconductor lasers is described by the parameter T_0 termed as 'characteristic temperature' and defined as

$$T_0 = \left(\frac{\partial \ln j_{th}}{\partial T} \right)^{-1}. \quad (4)$$

As clear from (4), the higher T_0, the more temperature-stable is j_{th}.

In CQWLs, the temperature dependence of j_{th} is primarily due to such dependence of the parasitic recombination current density in the entire OCL, $j_{spon,th}^{outside}$, and hence T_0 is low. In the ABL QW laser without intermediate layers, the temperature dependence of j_{th} is merely due to such dependence of the recombination current density in the QW, j_{spon}^{QW}, and hence T_0 is very high (ideally, T_0 calculated for j_{spon}^{QW} is equal to T – see [23]). In the ABL QW laser with intermediate layers, the temperature dependence of j_{th} is due to such dependence of both recombination current densities in and outside the QW. For the cavity lengths considerably exceeding the shortest cavity length (the minimum tolerable cavity length below which the lasing is impossible to attain – see [36]), the contribution of the parasitic recombination in the intermediate layers is small and hence T_0 is high also in this ABL QW laser [23]. This is illustrated in Figure 4, which shows the calculated T_0 against cavity.

Figures 6 and 7 show the threshold characteristics measured in our experimental ABL QW laser structure with intermediate layers [the structure of Figure 5(b)] – T_0 against reciprocal cavity length, and T_0 and j_{th} against temperature. For comparison, the characteristics measured for the reference CQWL structure [the structure of Figure 5(a)] are also presented. As seen from the figures, T_0 is considerably higher in the ABL QW laser as compared to the reference CQWL. In particular, at the operating temperature 20 ºC, T_0 is 143 K in the ABL QW laser while it is 99 K in the reference CQWL.

4. Power characteristics

The LCC of a diode laser (the output optical power P versus injection current density j) is given by

$$P(j) = \frac{\hbar\omega}{e} S (j - j_{th}) \eta_{int}(j), \quad (5)$$

where $\hbar\omega$ is the photon energy, $S = WL$ is the cross-section of the junction, W is the lateral size of the device, L is the cavity length, and $\eta_{int}(j)$ is the internal differential quantum efficiency (efficiency of stimulated recombination).

In the CQWL, the internal quantum efficiency is a decreasing function of the injection density. The following expression was derived for η_{int} in [37]–[39]:

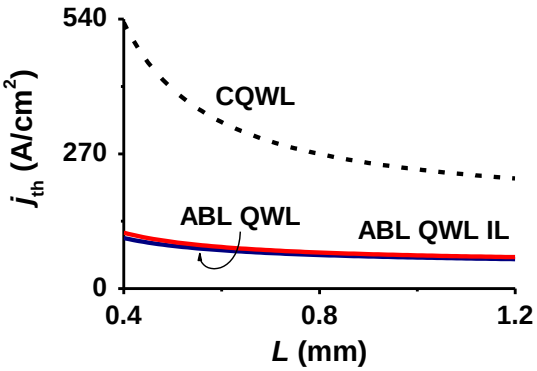

Figure 2. Threshold current density vs. cavity length in the ABL QW lasers without and with intermediate layers and reference conventional quantum well laser (CQWL).

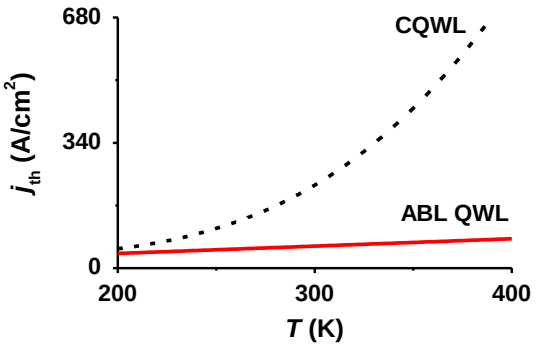

Figure 3. Threshold current density vs. temperature in the ABL QW laser without intermediate layers and reference CQWL.

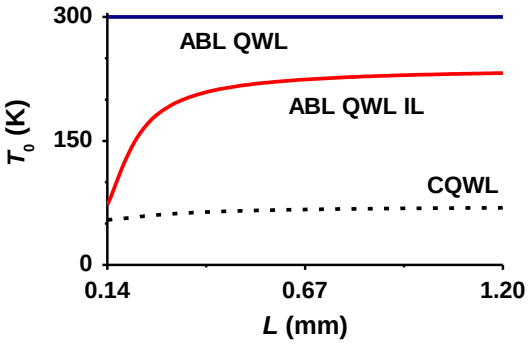

Figure 4. Characteristic temperature vs. cavity length in the ABL QW lasers without and with intermediate layers and reference CQWL.

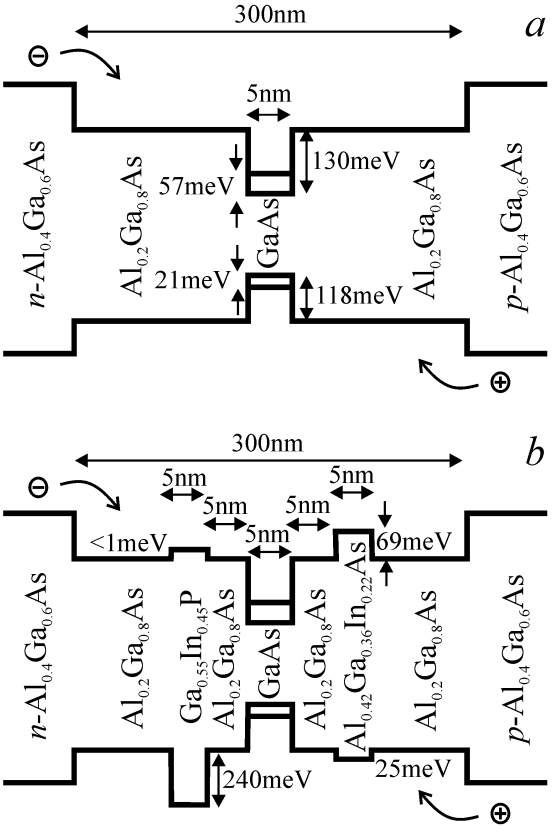

Figure 5. Energy band diagrams of the experimental structures: (a) reference CQWL and (b) ABL QW laser with intermediate layers. The lasing wavelength at 20 °C is 833.8 nm in the CQWL and 835.6 nm in the ABL QW laser.

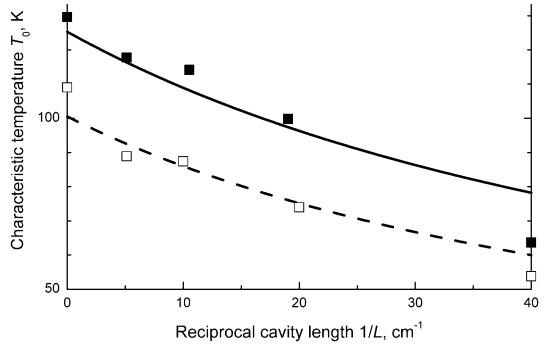

Figure 6. Experimental (symbols) and calculated (curves) dependences of the characteristic temperature on the reciprocal cavity length in the ABL QW laser with intermediate layers (solid curve, dark squares) and reference CQWL (dashed curve, open squares).

$$\eta_{\text{int}}(j)=\left[\frac{1}{2}+\frac{j_{\text{spon, th}}^{\text{outside}}}{\langle j_{\text{capt, th}}\rangle_{\text{harmon}}}+\sqrt{\left(\frac{1}{2}+\frac{j_{\text{spon, th}}^{\text{outside}}}{\langle j_{\text{capt, th}}\rangle_{\text{harmon}}}\right)^2+\frac{j_{\text{spon, th}}^{\text{outside}}}{\langle j_{\text{capt, th}}\rangle_{\text{geom}}}\frac{j-j_{\text{th}}}{\langle j_{\text{capt, th}}\rangle_{\text{geom}}}}\right]^{-1}, \quad (6)$$

where $\langle j_{\text{capt, th}}\rangle_{\text{harmon}}$ and $\langle j_{\text{capt, th}}\rangle_{\text{geom}}$ are the harmonic and geometric means of the current densities $j_{\text{capt, n, th}}$ and $j_{\text{capt, p, th}}$ of electron and hole capture into the QW at the lasing threshold,

$$\frac{1}{\langle j_{\text{capt, th}}\rangle_{\text{harmon}}}=\frac{1}{2}\left(\frac{1}{j_{\text{capt, n, th}}}+\frac{1}{j_{\text{capt, p, th}}}\right), \quad (7)$$

$$\langle j_{\text{capt, th}}\rangle_{\text{geom}}=\sqrt{j_{\text{capt, n, th}}\ j_{\text{capt, p, th}}}\ . \quad (8)$$

As seen from (6), the higher the parasitic recombination current density at the lasing threshold, $j_{\text{spon,th}}^{\text{outside}}$, the stronger the decrease in η_{int} with increasing j. Hence, η_{int} decreases considerably with j and the LCC is strongly sublinear in the CQWL. As already mentioned above, $j_{\text{spon,th}}^{\text{outside}}$ is very low in the ABL QW laser with intermediate layers and simply zero in the ABL QW laser without intermediate layers. Hence, η_{int} decreases only slightly with increasing j in the ABL QW laser with intermediate layers and constant (unity) in the ABL QW laser without intermediate layers; consequently, the LCC is just slightly sublinear in the ABL QW laser with intermediate layers and virtually linear in the ABL QW laser without intermediate layers. This is illustrated in Figures 8-10, which present the following characteristics calculated as functions of the injection current: the parasitic recombination current outside the QW, the internal differential quantum efficiency, and the LCC.

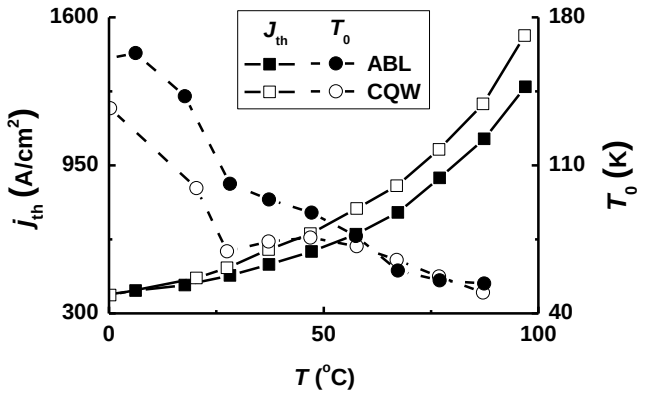

Figure 7. Experimental threshold current density (squares, left axis) and characteristic temperature (circles, right axis) vs. temperature: dark symbols – ABL QW laser with intermediate layers, open symbols – reference CQWL. The cavity length is 0.5 mm.

Figure 12 shows the experimental LCC in the ABL QW laser and reference CQWL of Figure 11. As seen from Figure 12, at both operating temperatures 20 and 60 ºC, the LCC is more linear and the output power is higher in the ABL laser.

Figure 13 shows the experimental wall-plug efficiency in the ABL QW laser with intermediate layers and reference CQWL of Figure 5. As seen from Figure 13, at both operating temperatures 20 and 75 ºC, the efficiency is distinctly higher in the ABL laser.

5. Conclusions

We have presented an overview of our theoretical and experimental work on a novel type of semiconductor lasers – quantum well (QW) lasers with asymmetric barrier layers (ABLs). Our experimental work supports our theoretical derivations — ABL QW lasers demonstrate superior operating characteristics as compared to conventional QW lasers. In particular, the threshold current is lower and more temperature-stable, the LCC is more linear, and the wall-plug efficiency is higher in ABL lasers.

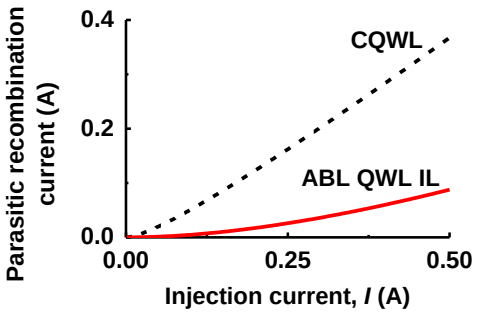

Figure 8. Parasitic recombination current vs. injection current in the ABL QW laser with intermediate layers and reference CQWL.

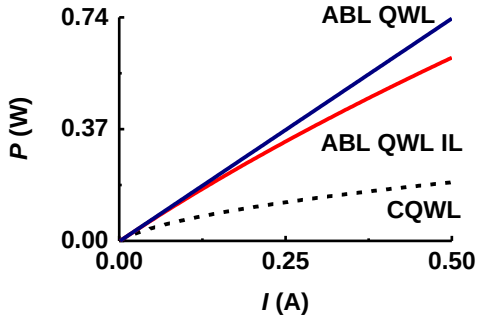

Figure 10. Light-current characteristic in the ABL QW lasers without and with intermediate layers and reference CQWL.

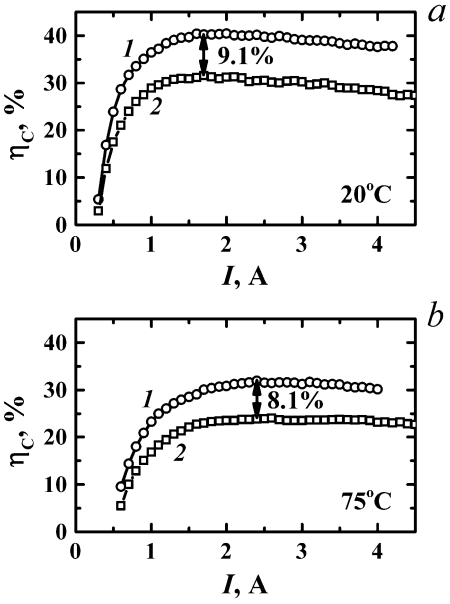

Figure 13. Experimental wall-plug efficiency vs. injection current in (1) the ABL QW laser with intermediate layers and (2) reference CQWL of Figure 5 at (a) 20 and (b) 75°C.

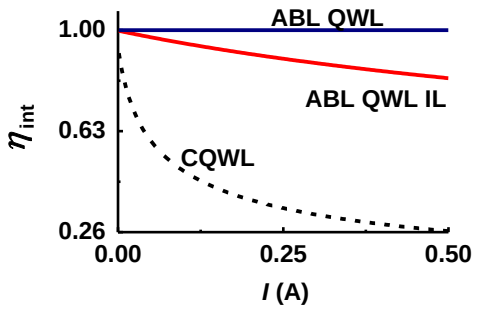

Figure 9. Internal differential quantum efficiency vs. injection current in the ABL QW lasers without and with intermediate layers and reference CQWL.

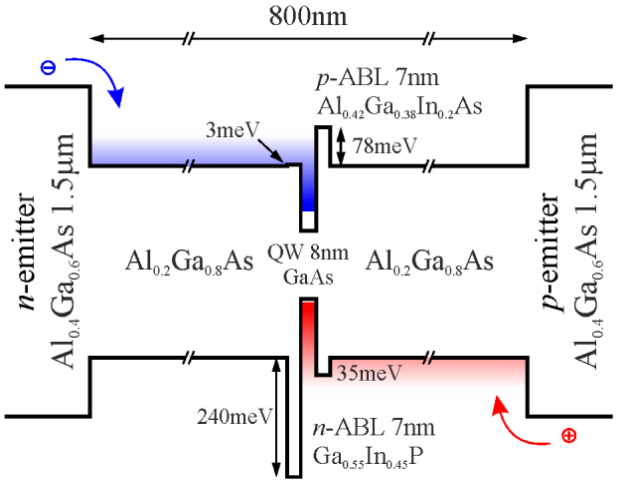

Figure 11. Energy band diagram of the experimental ABL QW laser used for the measurements in Figure 12.

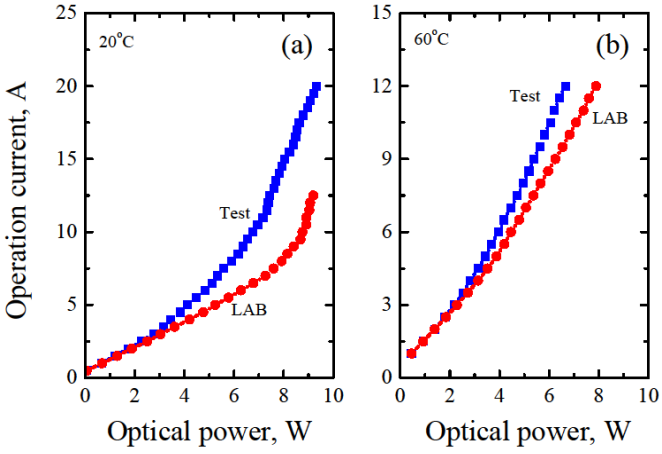

Figure 12. Operating current vs. output optical power measured in the ABL QW laser of Figure 11 and CQWL at 20ºC (a) and 60ºC (b).

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