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RESEARCH ARTICLE

Scalabilities of LEDs and VCSELs with tunnel-regenerated multi-active region structure

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Abstract Scalabilities of light-emitting diodes (LEDs) and vertical-cavity surface-emitting lasers (VCSELs) with tunnel-regenerated multi-active-region (TRMAR) structure were investigated. It was found that the output optical power and quantum efficiency of these new LEDs with TRMAR increased with the number of its active regions, but the threshold gain and threshold current density decreased. However, for VCSELs with TRMAR, the differential quantum efficiency and optical power increased with the number of the active region. The results suggest that LEDs and VCSELs with the TRMAR structure have some potential advantages over the conventional LEDs or VCSELs in high internal quantum efficiency, low heat generation, high round-trip gain, and so on. These advantages will make TRMAR LEDs or VCSELs more attractive for the industrial application.

Keywords tunnel junction, cascade, scalability, light-emitting diodes (LEDs), vertical-cavity surface-emitting lasers (VCSELs)

1 Introduction

The tunnel-regenerated multi-active-region (TRMAR) structure was proposed and successfully applied to several optoelectronic devices, such as light-emitting diodes (LEDs) [1], laser diodes (LDs) [2,3] and vertical-cavity surface-emitting lasers (VCSELs) [4]. TRMAR LEDs showed high brightness and high wall-plug efficiency. TRMAR LDs also presented high output power, low vertical divergence, and high cavity optical damage (COD) level, which usually limit conventional LDs to further improve their output power. For TRMAR VCSELs, the high round-trip gain was achieved by stacking the active regions to resolve the low round-trip gain of the conventional single active layer VCSEL. TRMAR structure could solve the problems or break through the limitations existed in the conventional single active layer structure essentially and then improve these optoelectronic device performances [5–8].

In this paper, the scalability of using the TRMAR structure as a function of the number of active regions was investigated not only in typical spontaneous and stimulated emission optoelectronic devices, more specially, in the surface-emitting LEDs and VCSELs. For LEDs, the quantum efficiency, output optical power, leakage current and heating caused by the leakage were analyzed in relation with the active layer number. Likewise, the threshold gain, power, differential quantum efficiency, and threshold current density were studied for VCSELs.

2 Basic structure and working mechanism

Figure 1 shows a schematic physical structure of the TRMAR structure (Fig. 1(a)) and along with the corresponding energy band diagram (Fig. 1(b)). The detailed working mechanism of TRMAR structure was described in Ref. [9]. For VCSELs, the additional requirement is that tunnel junctions should be located at the nodes of standing waves in order to reduce optical absorption. The most obvious feature of the TRMAR structure is the tunnel junctions sandwiched between the conventional active regions in p-i-n structures. One electron-hole pair can generate photons N_A times when carriers are regenerated at the reverse-biased tunnel junctions, N_A is the number of active regions. This mechanism increases the internal quantum efficiency N_A times over that of conventional single active layer devices, such as LEDs and VCSELs.

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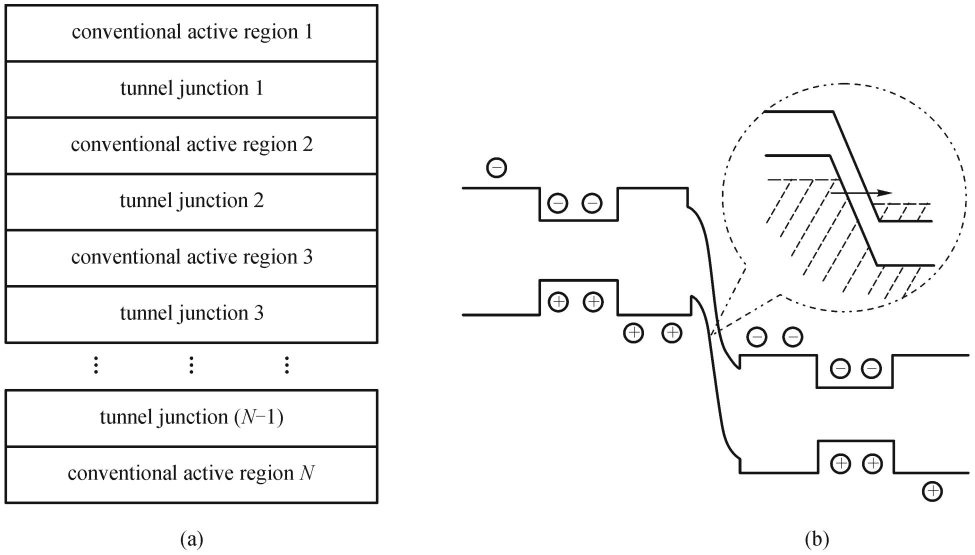

Fig. 1 Schematic structure (a) and its corresponding energy band diagram (b) of TRMAR structure

3 LED with TRMAR structure

3.1 Quantum efficiency and optical power of TRMAR LEDs

For a conventional single active layer LED, optical output power P_1 is [10, 11]

$$P_1 = \eta_c\eta_i\eta_r\frac{h\nu}{q}I = \eta_{ex}\frac{h\nu}{q}I, \tag{1}$$

where η_c,η_i,η_r are extraction efficiency, injection efficiency and radiation efficiency, respectively. η_{ex} is external quantum efficiency , $h\nu$ is photonic energy, q is electron charge, and I is injection current.

As calculating the output power of TRMAR LEDs with N_A active regions, the following assumptions are made: η_c,η_i,η_r are the same for each sub active region, the absorption of tunnel junction is small enough to be neglected, the loss due to multiple internal reflection and absorption is ignored. The power, P_2, in a one-dimension case that can be expressed simply as the N_A times of internal quantum efficiency in Eq. (2).

$$P_2 = N_A\eta_c\eta_i\eta_r\frac{h\nu}{q}I = N_A\eta_{ex}\frac{h\nu}{q}I = N_AP_1. \tag{2}$$

Clearly, the optical output power of TRMAR LEDs will be N_A times of that of conventional LEDs at the same current injection.

However, the absorption usually exists in the tunnel junctions. For TRMAR LEDs with a distributed Bragg reflector (DBR) structure, the optical output power in the vertical direction, P_3, can be described as

$$P_3 = P_1\left(1 + R\mathrm{e}^{-(N_A-1)\alpha L}\right)\sum_{m=1}^{N_A}\mathrm{e}^{-(m-1)\alpha L}, \tag{3}$$

where α is the absorption coefficient, L is the absorption length, R is the reflectivity of the DBR. Using a GaAs tunnel junction as an example, the doping densities for p-type and n-type side are taken as 1×10^{20} and 1×10^{18} cm^{-3}, respectively. The thickness of each side is assumed to be about 20 and 30 nm, respectively. The α of GaAs will be about 10^5 cm^{-1} for visible wavelengths. In this case, the free carrier absorption due to heavy doping is relatively small and can be neglected compared with the interband absorption.

Figure 2 shows the calculated results from Eq. (3). If the reflectivity R of the DBR is designed to be 70%, then it can be found that the optical power of TRMAR LEDs with two active regions is about 1.35 times larger than that of conventional LEDs. The optical power will increase with the number of active regions until five active regions because of two opposing trends of gain and loss. For five active regions and beyond, the optical power is saturated at about 1.5 times larger than that of a conventional single active layer LED.

Further, the TRMAR structure was examined in detail. Under strong electronic field in the tunnel junction, electron-hole pairs are separated to the opposite sides very fast from each other. The electron is swept to the n-type side, and the hole to the p-type side. The electrons and holes will inject to the next active region to repeat the recombination process. So are the recombined and subsequently regenerated carriers which repeat the process in the next active region. During this process, there will be some unavoidable loss, such as interface defects. By

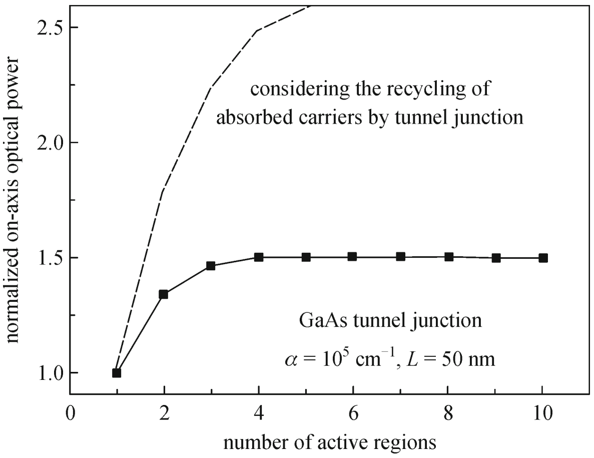

Fig. 2 Dependence of on-axis optical power on number of active regions for LEDs with DBR structure. The difference between dashed line and solid line with square is that for the former, absorbed carriers by tunnel junctions are reused, while for the latter, absorbed carriers occurred at the tunnel junction is considered as loss

ignoring these losses, the on-axis optical power was modified as shown in Fig. 2 by dashed line. The other line with square in Fig. 2 is closed to the actual effect of the TRMAR LEDs. By the above analyses, it can be obtained that the quantum efficiency and optical power of TRMAR LEDs could be much larger than those of conventional single active layer LEDs In addition, it can be also concluded that the tunnel junction can be regarded as the generation source for carrier recycling.

3.2 VCSEL with TRMAR structure

The physical difficulty in VCSELs is small round-trip gain due to thin gain region compared with edge-emitting lasers. And the small round-trip gain necessitates a high threshold current, which results in low optical output power.

In TRMAR VCSELs, the length that the stimulated light traverses through the active regions is N_A times of that of conventional single active layer VCSELs, which gives the round-trip gain of TRMAR VCSELs of approximately N_A times larger than that of a conventional single active layer VCSEL.

Assuming that the number of quantum wells (QWs) in each active region, the relative position in the standing wave of each sub QWs, and the mean mirror reflectivity R of DBR is the same as that of conventional VCSELs, the nodes of the standing waves are further assumed to be located at the tunnel junctions, the threshold modal gain g_{th2} of a TRMAR VCSEL having N_A active regions can be expressed as below:

$$g_{th2} = g_{th1} + (\alpha_i L_d + A_m)\left(\frac{1}{N_A} - 1\right), \tag{4}$$

and

$$A_m = \ln(1/R), \tag{5}$$

where g_{th1} is the threshold modal gain of conventional VCSELs, α_i is the internal optical loss, L_d is the effective length of DBR, and A_m is the mirror loss.

If $\alpha_i = 10$ cm^{-1}, $R = 99.95\%$, Eq. (4) gives g_{th2} in Fig. 3, showing that g_{th2} decreases with the number of the active regions and the g_{th2} required for the case of two active regions is only about half of a conventional single layer VCSEL.

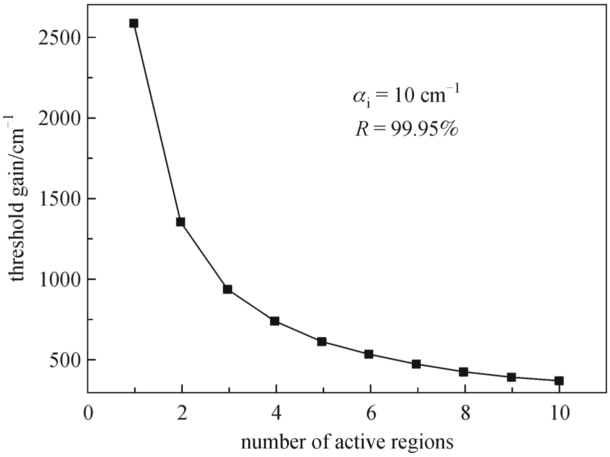

Fig. 3 Dependence of threshold gain on number of active regions

The threshold current density J_{th1} of conventional VCSELs can be expressed as

$$J_{th1} = J_{tr}\exp\left(\frac{g_{th1}}{g_0}\right), \tag{6}$$

where J_{tr} is the transparent current density, g_0 is the gain coefficient. J_{tr} for TRMAR VCSELs is almost the same as that of conventional VCSELs because the relative poison of the standing wave keeps no change in the TRMAR VCSELs. Then, the J_{th2} of TRMAR VCSELs can be given by

$$J_{th2} = J_{tr}\exp\left(\frac{g_{th2}}{g_0}\right) = J_{th1}\exp\left(\frac{g_{th2} - g_{th1}}{g_0}\right) = J_{th1}\exp\left(\frac{(\alpha_i L_d + A_m)\left(\frac{1}{N_A} - 1\right)}{g_0}\right). \tag{7}$$

For 8 nm strained GaAs/InGaAs multiple QWs (MQWs), $g_0 = 1200$ cm^{-1}, and assume that $J_{th} = 2$ kA/cm^2, then the J_{th2} from Eq. (7) is given in Fig. 4. The threshold current density of TRMAR VCSEL decreases with the number of active regions.

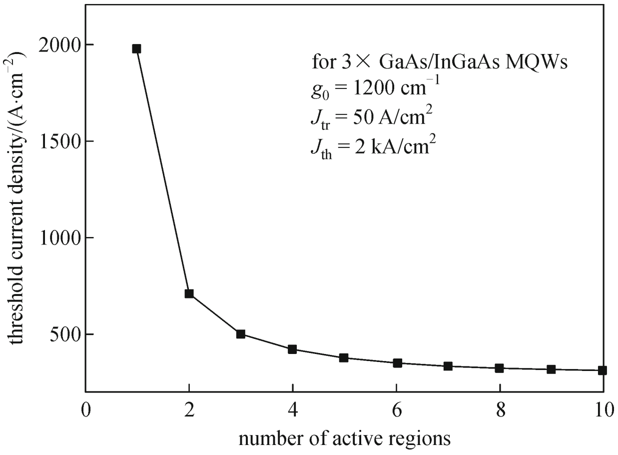

Fig. 4 Dependence of calculated threshold current density on number of active regions

Differential quantum efficiency η_{d} is another important parameter to evaluate the performance of a VCSEL. For a conventional single active layer VCSEL, we have

$$\eta_{\mathrm{d}} = \eta_{\mathrm{i}} \frac{\alpha_{\mathrm{m}}}{\langle \alpha_{\mathrm{i}} \rangle + \alpha_{\mathrm{m}}}, \tag{8}$$

where η_{i} is the quantum efficiency, $\alpha_{\mathrm{m}} = \frac{\ln\left(\frac{1}{R}\right)}{L}$ is the mirror loss, $R = \sqrt{R_1 R_2}$ is the effective mean mirror reflectivity, L is the cavity length, $\langle \alpha_i \rangle$ is the net internal optical loss. In VCSELs,

$$\langle \alpha_i \rangle = \frac{\alpha_{\mathrm{a}} L_{\mathrm{a}} + \alpha_{\mathrm{p}} L_{\mathrm{p}} + \alpha_{\mathrm{d}}(d_{\mathrm{dff1}} + d_{\mathrm{eff2}})}{L_{\mathrm{eff}}},$$

which includes three components of the loss from the active, passive, and DBR regions, respectively. In this paper, for 1-λ conventional VCSELs, L_{eff} is the effective length which is 1.2 μm, R = 99.5%, $\eta_{\mathrm{i}} = 0.7$, $\alpha_{\mathrm{i}} = 10\,\mathrm{cm}^{-1}$, and the effective length of DBR is about 0.45 μm.

For TRMAR VCSELs with N_{A} active regions, assuming the same η_{i} for each active region, then the η_{d2} can be shown as

$$\eta_{\mathrm{d2}} = N_{\mathrm{A}} \eta_{\mathrm{i}} \frac{A_{\mathrm{m}}}{\alpha_{\mathrm{i}}[N_{\mathrm{A}}(L_{\mathrm{a}} + L_{\mathrm{p}}) + L_{\mathrm{d}}] + A_{\mathrm{m}}}. \tag{9}$$

Figure 5 gives the dependence of η_{d2} on the N_{A} for variant$\langle \alpha_{\mathrm{i}} \rangle$'s 1, 5, 10, and 50 cm^{-1}, respectively, showing η_{d2} increasing with N_{A}. Clearly, the lower the $\langle \alpha_{\mathrm{i}} \rangle$ is, the higher the η_{d2} becomes.

For the optical output power P_0, a conventional single active layer VCSEL is given by

$$P_0 = \eta_{\mathrm{d}} \frac{\hbar \nu}{q} (I - I_{\mathrm{th}}), \tag{10}$$

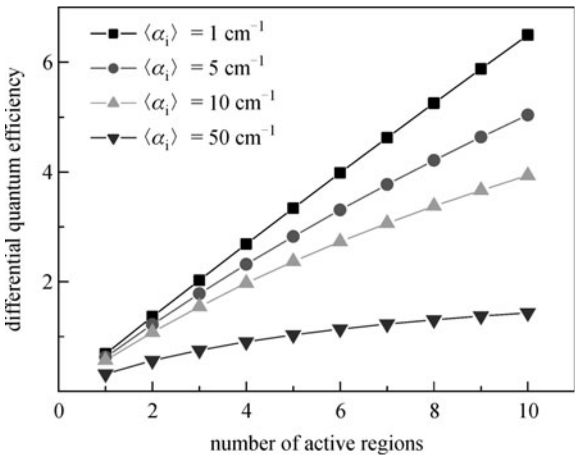

Fig. 5 Dependence of differential quantum efficiency on number of active regions when $\langle \alpha_{\mathrm{i}} \rangle$ was chosen to be 1, 5, 10, and 50 cm^{-1}, respectively

where $\hbar \nu$ is the photon energy, q is the electron charge, I is the bias current, and I_{th} is the threshold current.

In TRMAR VCSELs, we simply replace η_{d} by η_{d2} and I_{th} by I_{th2},

$$P_{02} = \eta_{\mathrm{d2}} \frac{\hbar \nu}{q} (I - I_{\mathrm{th2}}). \tag{11}$$

Assuming that $\langle \alpha_{\mathrm{i}} \rangle$ = 10 cm^{-1} and R = 99.5%, Fig. 6 shows P_{02} increasing with N_{A} at the injected current I = 10 mA. Based on Eqs. (9) and (11), it can be concluded that the smaller the internal loss, or the shorter the cavity length, the more significant the increase of the power with N_{A} becomes; the superiority of the TRMAR VCSELs could be incarnated very well.

From the analyses above, as the differential quantum efficiency η_{d} and the optical output power P_{02} of the TRMAR VCSELs increase with N_{A}, as the threshold gain

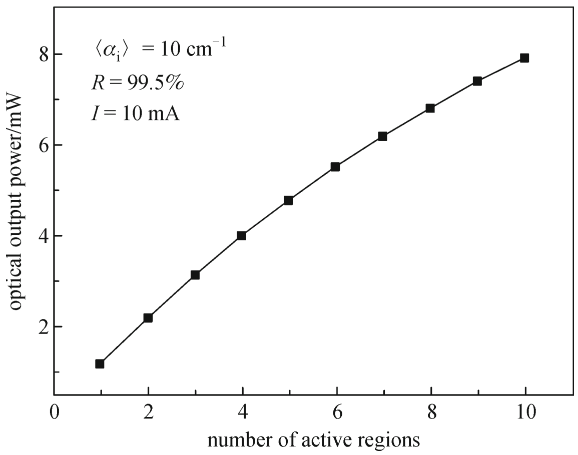

Fig. 6 Dependence of calculated optical output power on number of active regions when $\langle \alpha_{\mathrm{i}} \rangle$ was chosen to be 10 cm^{-1}

$g_{\mathrm{th}2}$ and the threshold current density $J_{\mathrm{th}2}$ decrease with N_{A}, the calculated results demonstrate that the TRMAR VCSELs will have high optical output power and high modulation frequency, which are two important performances in the all-optical communication.

4 Conclusions

In this paper, scalabilities of TRMAR LEDs and VCSELs were studied. For both spontaneous and stimulated emission processes, the TRMAR structure shows its potential superiority over the conventional LEDs or VCSELs in high internal quantum efficiency, low heat generation, high round-trip gain, etc. These advantages will make TRMAR LEDs or VCSELs more attractive for industrial application.

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