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The scalability of the tunnel-regenerated multi-active-region light-emitting diode structure*

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The scalability of the tunnel-regenerated multi-active-region (TRMAR) structure has been investigated for the application in light-emitting diodes (LEDs). The use of the TRMAR structure was proved theoretically to have unique advantages over conventional single-active-layer structures in virtually every aspect, such as high quantum efficiency, high power and low leakage. Our study showed that the TRMAR LED structure could obtain high output power under low current injection and high wall-plug efficiency compared with the conventional single-active-layer LED structure.

Keywords: scalability, tunnel junction, regeneration
PACC: 7360L, 7300, 7000

1. Introduction

The tunnel-regenerated multi-active-region (TRMAR) structure was proposed and has been successfully applied to several optoelectronic devices, such as light-emitting diodes (LEDs), laser diodes (LDs) and vertical-cavity surface-emitting lasers (VCSELs).[1−5] TRMAR LEDs show high brightness and high wall-plug efficiency. TRMAR LDs also show high output power, low vertical divergence, and high catastrophic optical damage level, which usually put a limit to conventional LDs in further improving their output power. For TRMAR VCSELs, the high round-trip gain was achieved by stacking the active regions in resolving the low round-trip gain of the conventional single-active-layer VCSEL. TRMAR structure has proved to have the ability to solve the problems or essentially to break through the limitations existing in the conventional single-active-layer structure, and then improves these optoelectronic device performances.

In this paper, the scalability of the TRMAR LED structure as a function of the number of active layers is investigated. The important parameters for evaluating the LED performance, such as quantum efficiency, output optical power, leakage current and heating caused by the leakage, are analysed in relation with the active layer number.

2. Basic structure and working mechanism

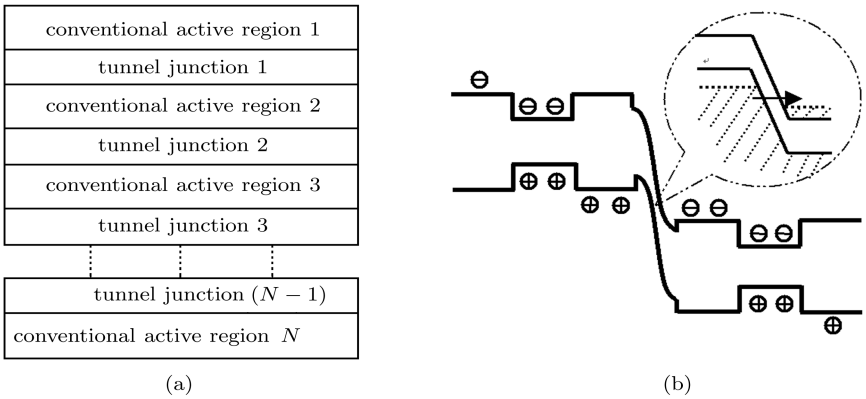


Fig.1. Schematic structure (a) and its corresponding energy band diagram (b) of the tunnel-regenerated multi-active-region (TRMAR) structure.

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Figure 1 shows a schematic construction of the TRMAR structure (a) and the corresponding energy band diagram (b). Its working mechanism of TRMAR structure has been described in detail in Ref.[6]. The most obvious feature of the TRMAR structure is the tunnel junctions sandwiched in between the conventional active layers in p-i-n structures. One electron-hole pair could generate photons $N_{\rm a}$ times when the carriers are regenerated at the reverse-biased tunnel junctions; $N_{\rm a}$ is the number of the active regions. This mechanism increases the internal quantum efficiency $N_{\rm a}$ times over that of a conventional single-active-layer device.

3. Advantages of TRMAR LEDs

For a conventional single-active-layer LED, the optical output power P_1 is

$$P_1 = \eta_{\rm c}\eta_{\rm i}\eta_{\rm r}\frac{hv}{q}I = \eta_{\rm ex}\frac{hv}{q}I, \qquad (1)$$

where $\eta_{\rm c}, \eta_{\rm i}, \eta_{\rm r}$ are the extraction efficiency, injection efficiency and radiation efficiency, respectively; $\eta_{\rm ex}$ is the external quantum efficiency of LEDs, $h\nu$ is the photonic energy, q is the electron charge, and I is the injection current.

In calculating the output power of TRMAR LEDs that have $N_{\rm a}$ active layers, we make the following assumptions: $\eta_{\rm c}, \eta_{\rm i}$, and $\eta_{\rm r}$ have the same values in all the active sub-regions; the absorption of tunnel junction is small enough to be neglected; the loss of multiple internal reflection and absorption in the active regions is ignored. The power, P_2, in the one-dimensional case can be expressed simply as the $N_{\rm a}$ times of internal quantum efficiency as follows:

$$P_2 = N_{\rm a}\eta_{\rm c}\eta_{\rm i}\eta_{\rm r}\frac{hv}{q}I = N_{\rm a}\eta_{\rm ex}\frac{hv}{q}I = N_{\rm a}P_1. \qquad (2)$$

Figure 2 shows the calculated results of Eq.(2), assuming that the optical power P_1 of a conventional single-active-layer LED is normalized to unity. Clearly, the optical output power of TRMAR LEDs will be $N_{\rm a}$ times that of the conventional LEDs at the same current injection.

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

$$P_3 = P_1\left(1 + R{\rm e}^{-(N_{\rm a}-1)\alpha L}\right)\sum_{m=1}^{N_{\rm a}} {\rm e}^{-(m-1)\alpha L}, \qquad (3)$$

where α is the absorption coefficient, L the absorption length, R the reflectivity of the DBR. Using a GaAs tunnel junction as an example, the doping densities for the p-type and n-type sides are taken to be $1\times10^{20}\,{\rm cm}^{-3}$ and $1\times10^{18}\,{\rm cm}^{-3}$, respectively. The thicknesses of p- and n-type sides are assumed to be about 20 and 30 nm, respectively. The coefficient α of GaAs is about $10^5\,{\rm cm}^{-1}$ for visible wavelengths. In this case, the free carrier absorption due to heavy doping is relatively small and can be neglected as compared with the interband absorption.

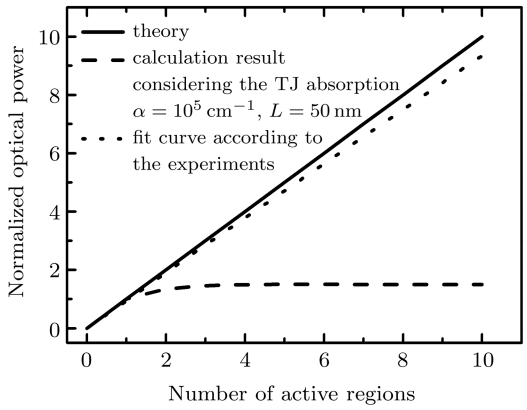


Fig.2. Dependence of the on-axis optical power on the number of active regions for the LEDs with the DBR structure. The straight line, calculated from Eq.(2), stands for the ideal case. When considering the absorption of the tunnel junction, the dashed line, according to Eq.(3), shows the relationship between output optical power and the number of active regions, where $\alpha = 10^5\,{\rm cm}^{-1}$, and the total thickness of GaAs tunnel junction $L = 50\,{\rm nm}$. The output power will saturate due to the strong interband absorption. The dotted line is the fit curve to the data extracted from experiment, indicating that the loss in the TRMAR LED structure is relatively small.

The dashed line in Fig.2 shows the calculated results from Eq.(3). If the reflectivity R of the DBR is designed to be 70%, then it can be seen 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 layers and beyond, the optical power is saturated at about 1.5 times larger than that of a conventional single-active-layer LED.

Let us examine the process in TRMAR structure further in detail. Under strong electronic field in the reverse-biased tunnel junction, electron-hole pairs are separated very fast from each other to the opposite sides. The electrons generated by photon absorption

in the tunnel junctions will be swept to the n-type side, and the holes to the p-type side. Then these electrons and holes will join into the conduction band and valence band in the next stage, respectively. This process is called carrier regeneration. From this point of view, the reverse-biased tunnel junctions in TRMAR structure could be regarded as the carrier generation source. These regenerated carriers will subsequently recombine with and regenerate photons again in the next active region. However, during this process, there will be some unavoidable loss such as that due to interface defects. The dotted line in Fig.2 shows the fit curve with the data extracted from our experiments,[4] which proves that the loss inside the TRMAR LED structure is relative small.

From the analyses above, two conclusions can be drawn. One is that the quantum efficiency and optical power of TRMAR LEDs could be much larger than those of conventional single-active-layer LEDs. The quantum efficiency can be much larger than one. The other is that the tunnel junction can be regarded as the generation source for carrier recycling.

Besides the larger values of output optical power and quantum efficiency, the leakage current level and heating of TRMAR LEDs are greatly reduced as compared with the conventional single-active-layer LED. At the same optical output power, the injected current for TRMAR LEDs is only $\frac{1}{N_a}$ times that of the conventional single-active-layer LEDs, and hence the carrier filling levels (or quasi Fermi levels) will be lowered. The lower the carrier filling level is, the lower the leakage current becomes, which is very important for materials with small band offsets.

Taking AlGaInP LEDs as an example, the electron band offset ΔE_c of the AlGaInP/AlInP interface is only about 2–3 kT at room temperature. For a single-active-layer structure, the electron leakage current density J_{n1} at this double heterojunction interface between a p-$(Al_{0.2}Ga_{0.8})_{0.5}In_{0.5}P$ active region and a p-type AlInP layer can be expressed as[7]

$$J_{n1} = qD_n \frac{N_{p0}}{L_n}, \tag{4}$$

$$N_{p0} = N_c \exp\left(\frac{E_{Fn} - \Delta E_c}{k_B T}\right), \tag{5}$$

$$D_n = \frac{kT}{q}\mu_n, \tag{6}$$

where D_n is the diffusion coefficient in the P-AlInP, N_{p0} is the electron concentration at the edge of P-AlInP layer, N_c is the effective density of states in the conduction band of the heterojunction, E_{Fn} is the electron quasi-Fermi energy level which is a function of the carrier concentration n_0, ΔE_c is the difference between the two conduction band energies at the heterojunction, and μ_n is electron mobility in P-AlInP, which is about 200 cm^2/V·sec, yielding an electron diffusion length L_n of about 4 μm.

For TRMAR LEDs with N_a active regions, in order to have the same optical output with that of conventional LEDs, the leakage current density can be expressed as

$$J_{n2} = qD_n N_c \exp\left(\frac{k_B T \ln\left(\frac{n_0}{N_c N_a}\right) - \Delta E_c}{k_B T}\right). \tag{7}$$

Figure 3 shows that the leakage current density J_{n2} in the p-P heterojunction decreases with the number of active layers. Clearly, this lowers the leakage current level and result in a lower heat generation and a higher efficiency, especially in the case of higher current injection.

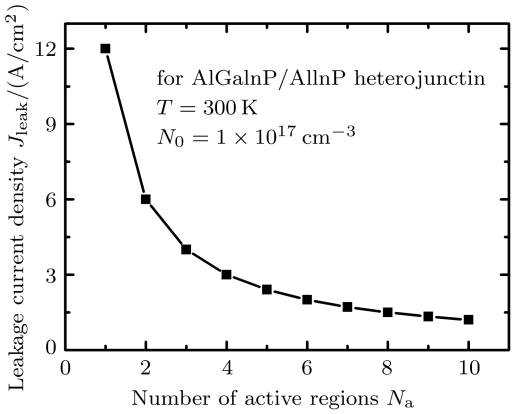


Fig.3. Dependence of the leakage current density on the number of active regions. With the increase of the number of active regions, the leakage current density is reduced due to the lower carrier filling in the each sub active regions.

Hence, a LED with TRMAR structure has a high quantum efficiency, which is approximately directly proportional to the number of the active regions and low heating due to lower carrier leakage level in the active region at the same optical output power. Such LEDs will yield high optical output power at low current injection and have high wall-plug efficiency at high current injection as compared with the conventional single-active-region LEDs.

4. Conclusion

In this paper, the scalability of TRMAR LED has been studied. It is shown that it has potential superiority to the conventional LEDs by high quantum efficiency, low carrier leakage, and low heat generation. These advantages will make TRMAR LEDs more attractive in the industrial applications.

Acknowledgments

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