Thermal Property of Tunnel Cascaded and Coupled Multi-Active Regions Laser Diodes

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Abstract

Tunnel cascaded and coupled multi-active regions laser diodes are novel high power laser diodes. This kind of laser diodes can achieve high output power at relatively low current density and overcome the main hindrance of the normal high power semiconductor lasers: catastrophic optical damage (COD) by increase the size of facula. Transient thermal property of these laser diodes has been calculated by using finite element method (FEM). Three kinds of laser diode structures, one active region, two active regions with one tunnel junction and three active regions with two tunnel junctions, are simulated. The calculated results are in agreement with the measured data. The result indicates that for tunnel cascaded and coupled multi-active regions laser diodes, temperature rising of the active region near the substrate is a little higher than that near heat sink. With active region number increasing, the temperature of the laser diodes rises but multi-active regions were fabricated on the uniform substrate, its thermal resistance is still smaller than that of series with the same number normal laser diodes.

Keywords: tunnel cascaded, laser diodes, thermal property, finite element method

1.Introduction

Great headway has been made in 980nm high power semiconductor lasers, and it have been widely applied in many important fields, such as communication, military, medicine, etc.. In those applications, thermal characteristic plays a very important role because it directly affects the reliability of the laser diodes. Since the temperature rising leads to a degradation of laser diode performance, an increase in the threshold current, a decrease in the radiation intensity, the shift of stimulated radiation modes and the reduction of the laser diode lifetime.

Tunnel cascaded and coupled multi-active regions laser diodes are novel high power laser diodes [1,2]. The structure schematic diagram and the energy band diagram show as Figure 1. The primary principle is that multi-active regions are fabricated on the uniform substrate orderly, and there is a tunnel junction between every two active regions, the aim is that the carriers recombining in previous active region can be regenerated through the reverse biased tunnel junction. Every pair of electron and hole injected from two electrodes of laser diode has a process of radiative recombination time after time in multi-active regions and generates multi-photons. This mechanism enhances quantum efficiency greatly and breaks though the theoretical utmost of quantum efficiency less than 1. Great progress and achievements have been obtained in the theoretic and experimental aspects. Those new type laser diodes can achieve high output power at relatively low current density and overcome the main hindrance of normal high power semiconductor lasers: catastrophic optical damage (COD) by increasing the size of facula. Compared with the normal laser diodes, the thermal characteristic of these laser diodes are much more important due to their high power output. Simultaneously its thermal

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property is incompletely like as the normal one due to its different structure, so it is necessary to investigate the thermal property of these laser diodes.

In this paper, the temperature distribution in the tunnel cascaded and coupled multi-active regions laser diodes is calculated by using the finite element method. To simply the calculation process, only one dimension model was discussed. In the active regions, nonradiative recombination and absorption of spontaneous emission are considered to be the dominant heat sources. In the capping layer and tunnel junction region, heat comes from the absorption of spontaneous emission transferred through active regions, while in other layers Joule heating is assumed to be the main heat source. The calculated results are in agreement with the measured data.

2. Theoretical model

2.1 Device structure

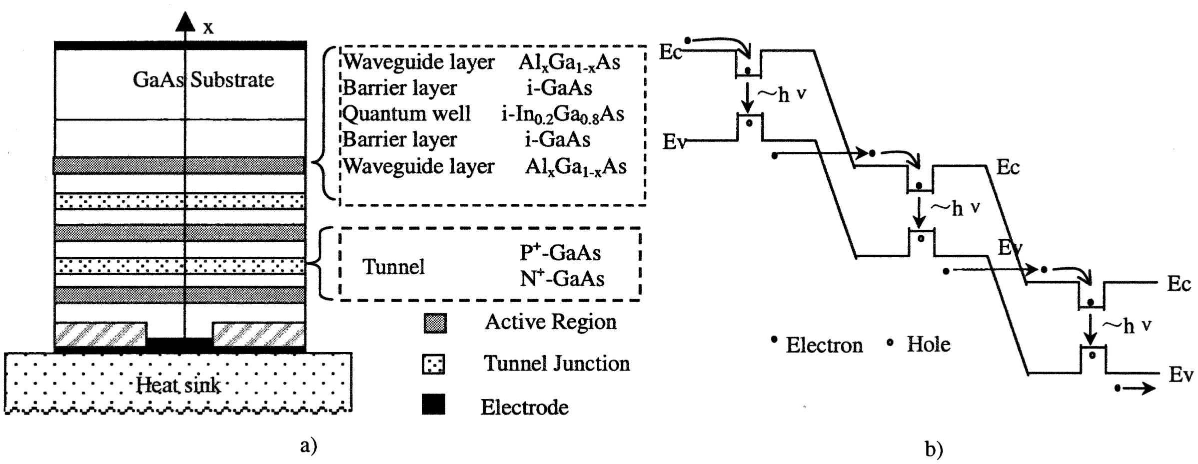

Figure 1: a) Schematic diagram of a three active regions semiconductor laser cascaded by tunnel junctions

b) Energy band diagram of a three active regions semiconductor laser cascaded by tunnel junctions

The laser diode structure with three active regions is shown in Figure 1: three $In_{0.2}Ga_{0.8}As$-GaAs strained quantum wells as active region; two heavy doping p-type GaAs and n-type GaAs as tunnel junction, all of the above layers grown on an n^+-GaAs substrate, with a Ti-Au contact on the p-type GaAs capping layer and Au-Ge-Ni contact on the back of the substrate for current injection. The well and barrier thicknesses are 8nm and 20nm,respectively, and the substrate thickness is 100μm. The thickness of n-type and p-type GaAs tunnel junction are 30nm and 10nm. The laser diode structure with two active regions is similar to this structure.

2.2 Thermal conduction equation

The temperature variation with time in the tunnel cascaded and coupled multi-active regions laser diode is the dynamic thermal conduction equation

$$\rho_i c_i \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{xi}\frac{\partial T}{\partial x}\right) + \rho_i Q, \tag{1}$$

With the boundary conditions

$$\begin{cases} T\big|_{x=0} = T_0 \\ \left.\dfrac{\partial T}{\partial x}\right|_{x=l} = 0 \end{cases}, \quad (2)$$

and the initial condition

$$T(t=0) = T_0, \quad (3)$$

Where T is the material temperature, t is time, ρ is the density of material, c is the specific heat of material, k is the thermal conductivity in x direction, l is the thickness of the laser diodes and Q is the heat generation ratio.

2.3 Heat source analysis

To solve the temperature distribution in tunnel cascaded and coupled multi-active regions laser diode, heat sources within the laser diodes must be quantitatively analyzed.

In comparison with the normal laser diodes, heat sources of this new type laser have its own characteristics. It consists of four parts: the active region, the capping layers, the tunnel junction, and other layers whose heat source comes of Joule heating.

2.3.1 Active region

In the active region, the main heat source comes of nonradiative recombination and absorption of spontaneous emission [3,4,5], which are together represented by

$$Q_{active} = \frac{V_j\left(1-\eta_{sp} f_{sp}\right)}{d_{active}}\left[j_{th} + \left(j - j_{th}\right)\left(1-\eta_i\right)\right] \quad (4)$$

Where d is the thickness of the active region; η_{sp} and η_i are the internal quantum efficiencies for spontaneous and stimulated emission, respectively; f_{sp} is a geometrical factor accounting for the escape of spontaneous light from the active region; j_{th} is the threshold current density in the center of the active region; V_j is the voltage drop at the p-n junction.

2.3.2 Capping layer

The above-mentioned spontaneous radiation is absorbed in the capping layer, and the heat power densities generated in this process may be expressed in the following way [3,5]

$$Q_{cap} = j^2 \rho_j + \frac{1}{2} \times \frac{V_j j_{th} \eta_{sp} f}{d_{active}} \quad (5)$$

In equ.5, the former denotes the quantity of heat coming of Joule heating, and the latter denotes the quantity of heat coming of spontaneous radiation absorption. ρ_j is the electrical resistivity of the capping layer.

2.3.3 Tunnel junction

Tunnel junctions are made up of heavy doping p-type GaAs and n-type GaAs. Free carriers absorption and strong field absorption of depletion layer can produce absorption loss. Through designing waveguide structure, light fields of tunnel junction are much weaker than that of other layers, so these heats, which are produced by absorption loss, are ignored. Tunnel junction's heat source comes from the absorption of spontaneous emission transferred through active regions and Joule heating arising from tunnel junction's electrical resistance. So heat power density of this layer can be expressed as

$$Q_{tunnel} = j^2 \rho_j + \frac{V_j j_{th} \eta_{sp} f}{d_{active}} \quad (6)$$

Where ρ_j is the electrical resistivity of tunnel junction and d_{active} is the thickness of Tunnel junction.

2.3.4 Other layer

In other layers of the device, only Joule heating is taken into account and their heat power densities can be expressed in the following way

$$Q_j = j^2 \rho_j \quad (7)$$

Where ρ_j is the electrical resistivity of the jth layer.

3.Results and discussion

According to above-mentioned analysis, three kinds of laser diode structures, one active region, two active regions with one tunnel junction and three active regions with two tunnel junctions, are simulated. Each individual layers' thickness, thermal conductivity, density, heat capacity, and resistance in laser diodes with three active regions show as Table 1. The other structures are similar to this structure. Other parameters which are used in calculation are: V_j=1.5V, j_{th}=200A/cm^2, j=3*j_{th}, η_{sp}=0.64, f_{sp}=0.53, η_i=0.95. Figure 2 shows the temperature distribution of laser diodes with one active region along x-axis direction at different time. While the operation time is very short, because of the highest thermal generation ratio in active region, there is a peak value of temperature and the capping layer's temperature and the substrate's temperature decrease in turn. Initially thermal doesn't exert an influence on the substrate. With lapse of time, thermal produced in active region is diffused towards the substrate and heat sink. Because of heat sink having favorable heat conduction and heat exchange with the environment being tiny, thermal is dissipated rapidly and it results in the temperature of the substrate rising gradually. Figure 3 is the temperature vs. time curve of every layer central point in single pulse operation. From the figure, we can see that temperature changing is the fastest in active region, the

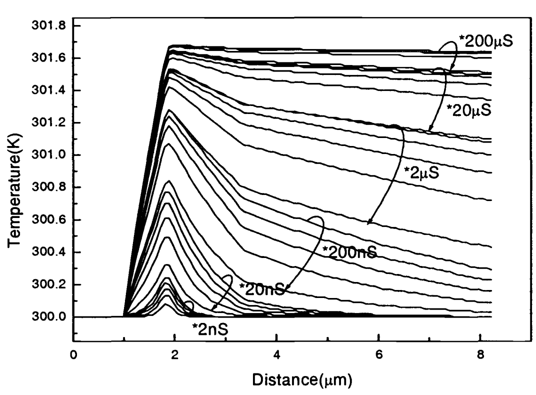

Figure 2: Transient temperature response of laser diode with one active region from 2nS to 1000uS along the x-axis direction.

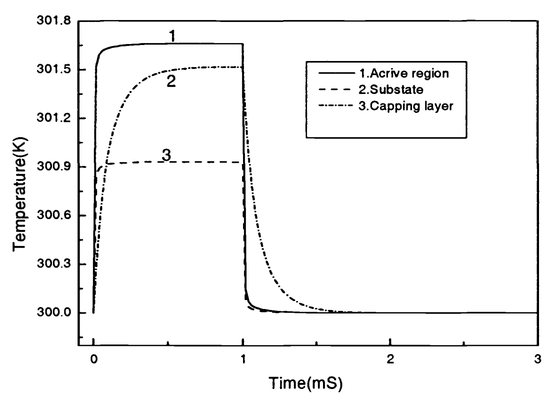

Figure 3: Transient thermal response of laser diode with one active region in single pulse operation.

second is the capping layer's temperature, and the substrate's temperature changing is the lowest.

Figure 4 shows the temperature distribution of laser diodes with two active regions along x-axis direction at different time. It is shown that in short time the heat source of every layer produces its temperature distribution. There are three peak values of temperature in two active regions and tunnel junction, and the temperature of two active regions is much higher than that of tunnel junction. With time increasing, this three regions work on each other and engender a piece of region where the temperature is relatively high. In this region, tunnel junction's temperature is the highest and two active region's temperatures are identical in the rough. With much time lapsing, no heat is educed from the substrate, so the temperature of active region near the substrate is appreciably higher than that near the heat sink. It can be illuminated from Figure 5.

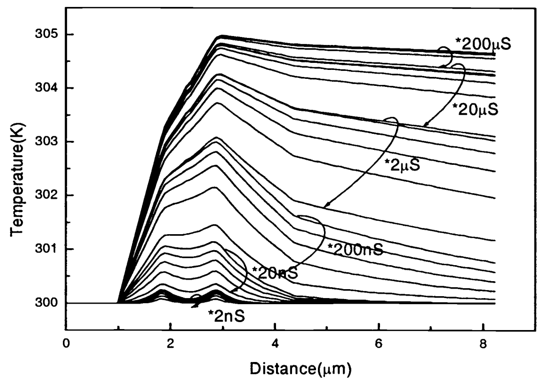

Figure 4: Transient temperature response of laser diode with two active regions from 2nS to 1000uS along the x-axis direction.

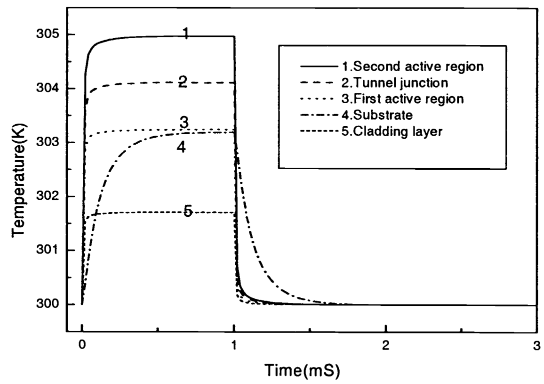

Figure 5: Transient thermal response of laser diode with two active regions in single pulse operation.

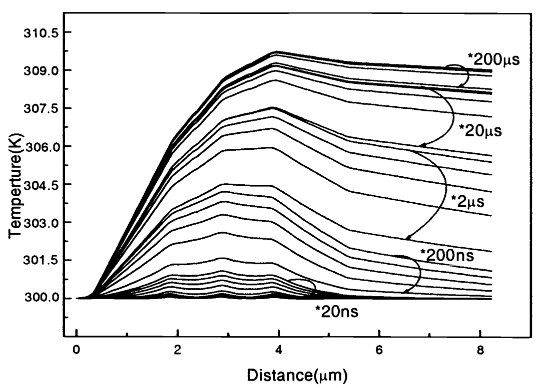

Figure 6: Transient temperature response of laser diode with three active regions from 2nS to 1000uS along the x-axis direction.

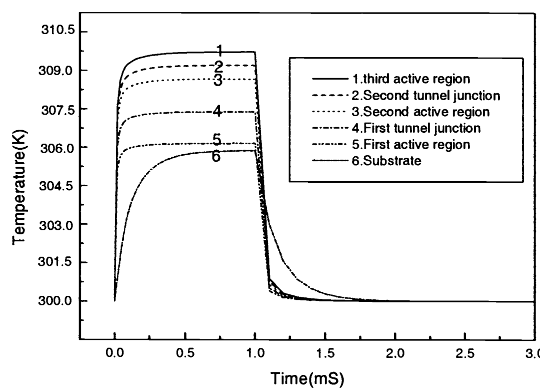

Figure 7: Transient thermal response of laser diode with three active regions in single pulse operation.

Figure 6,7 show the temperature distribution of laser diodes with three active regions, its temperature distribution trend is just like that of laser diode with two active regions. At first, the temperature variety rate of active region near heat sink has the slowest value in laser diode, the corresponding value of the active region near the substrate is slower, and the middle active region's value is the fastest. With the time increasing, the temperature of the active region near the substrate is higher than the part of the active region adjacent to the heat sink. It is because that thermal conductivity of the heat sink is higher than that of the substrate. The result also indicates that with active region number increasing, the temperature in the laser diode rises.

The laser diodes are measured with semiconductor laser test equipment. For temperature dependence of wavelength, we measure the wavelength shift in pulse width with 1000μS and frequency with 300Hz, and use the wavelength measured at 2μS as benchmark and on the basis of Equ.8, we educe the wavelength changing coefficient with temperature is 0.2766nm/K for wavelength 980nm. Using the wavelength shift value, the temperature rise can be deduced. The temperature raising value of two active regions laser diodes is 4.2K and the value of three active regions laser diodes is 8.6K, though those measured values are operated together by multi-active regions, it can reflect the temperature rising of laser diodes.

$$\frac{d\lambda}{dT} = -\frac{hc}{E_g^2}\cdot\frac{dE_g}{dT} = -\frac{dE_g}{dT}\cdot\frac{\lambda^2}{hc} \tag{8}$$

Table 1 Thickness, thermal conductivity, density, heat capacity, and resistance of the individual layers of laser diodes with three active regions[6]

Layer Number	Material	Thickness (μm)	Thermal Conductivity ($Wm^{-1}k^{-1}$)	Heat Capacity ($Jm^{-3}k^{-1}$)	Density (Kg m^{-3})	Resistance (Ωcm)
1	Au	0.2	301	132	19320	1.05e-11
2	GaAs	0.2	46	322	4318	1e-3
3	$Al_xGa_{1-x}As$	1.3	12.1	357.7	4852	3.1e-3
4	GaAs	17nm	46	322	4318	
5	$In_{-0.2}Ga_{0.8}As$	8nm	8.32	333.5	5376	
6	GaAs	17nm	46	322	4318	
7	$Al_xGa_{1-x}As$	1.6	12.1	357.7	4852	1.19e-3
8	N+-GaAs	30 nm	46	322	4318	6e-4
9	P+-GaAs	10 nm	46	322	4318	1e-3
10	$Al_xGa_{1-x}As$	1.6	12.1	357.7	4852	3.1e-3
11	GaAs	17nm	46	322	4318	
12	$In_{0.2}Ga_{0.8}As$	8nm	6.78	337.8	5396	
13	GaAs	17nm	46	322	4318	
14	$Al_xGa_{1-x}As$	1.6	12.1	357.7	4852	1.19e-3
15	N+-GaAs	30 nm	46	322	4318	6e-4
16	P+-GaAs	10 nm	46	322	4318	1e-3
17	$Al_xGa_{1-x}As$	400nm	12.1	357.7	4852	3.1e-3
18	GaAs	17nm	46	322	4318	
19	$In_{0.2}Ga_{0.8}As$	8nm	6.78	337.8	5396	
20	GaAs	17nm	46	322	4318	
21	$Al_xGa_{1-x}As$	1.6	12.1	357.7	4852	1.19e-3
22	GaAs	100	46	322	4318	9e-4

4.Conclusion

Using finite element method to solve the time-dependent thermal conduction equation, we have investigated the transient thermal properties of tunnel cascaded and coupled multi-active regions laser diodes. This analysis leads us to conclude that the temperature of the active region near heat sink is the lowest and the temperature of active region near the substrate is the highest in these laser diodes. With the active region number increasing, the temperature rising of laser diodes corresponds with its number. Because of multi-active regions being fabricated on the uniform substrate, thermal resistances of tunnel cascaded and coupled multi-active regions laser diodes are still smaller than that of series with the same number normal laser diodes. Familiar with the temperature distribution of the laser diodes is useful for optimizing the device structures and improving the device performance

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