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Temperature dependence of the threshold current for AlGaAs lasers grown by low temperature LPE

M. SÁNCHEZ, J.C. GONZÁLEZ, E. MARÍN
Faculty of Physics, DIEES–IMRE, University of Havana
San Lázaro y L, Vedado, La Habana, Cuba

P. DÍAZ*
Department of Physics, Centro de Investigación y de Estudios Avanzados del IPN
Apartado postal 14–740, 07000 México, D.F., México

AND

T.A. PRUTSKIJ
University of Puebla, CIDS–ICUAP, Puebla, México

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ABSTRACT. In the present work we study the temperature dependence of the threshold current density J_{th} in straight separate confinement heterostructure (SCH) lasers. The laser structures were grown by the low temperature liquid phase epitaxy (LT-LPE) technique. The threshold current of the devices was measured in a wide temperature interval (77–350 K) for conventional and quantum well (QW) lasers. In order to have a better characterization of the laser diodes and understanding of the results, theoretical estimations of the temperature dependence of J_{th} were performed. The theory takes into account three loss mechanisms: leakage current, non-radiative recombination from the L and X conduction band minima of the active layer material and Auger recombination. The experimental results fit quite well the theoretical predictions. Moreover, it will be shown that the mayor influencing factor in the threshold current density-temperature behavior is the leakage current. The relatively high values of the characteristic temperature T_0 obtained, prove that LT-LPE technique is a suitable one for the performance of laser diodes with a good thermal stability.

RESUMEN. Se presenta un estudio de la dependencia térmica de la densidad de corriente de umbral J_{th} para láseres de heteroestructuras con confinamiento separado (SCH) recto. Las estructuras láseres fueron crecidas por el método de epitaxia líquida a bajas temperaturas (LT-LPE). Se midió la corriente de umbral en un intervalo amplio de temperatura (77–350 K) en láseres del tipo convencional y del tipo de pozos cuánticos (QW). Para una mejor caracterización de los dispositivos y comprensión de los resultados se realizó un estudio teórico de la dependencia térmica de la J_{th}. El modelo teórico incluyó tres mecanismos de pérdidas: la corriente de fuga, la recombinación no radiativa desde los mínimos L y X de la banda de conducción del material de la zona activa del láser y la recombinación de Auger. Los resultados teóricos están en buena concordancia con los datos experimentales y permitió concluir que el mecanismo de mayor influencia en la dependencia térmica de la densidad de corriente de umbral J_{th} es la corriente de fuga. Los valores relativamente altos de la temperatura característica T_0 obtenidos, prueban que la técnica LT-LPE es adecuada para la obtención de láseres con buena estabilidad térmica.

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*Permanent address: Faculty of Physics, DIEES–IMRE, University of Havana. San Lázaro y L, Vedado, La Habana, Cuba.

1. Introduction

The liquid phase epitaxy (LPE) technique at low temperature regimes (LT-LPE) for the growth of multilayer semiconductor heterostructure lasers in the AlGaAs system has been used successfully for the performance of good laser diodes. Using this technique we have reported a threshold current density (J_{th}) value of 192 A/cm^2 for a laser diode with cavity length $L = 1,15$ mm at $\lambda = 848$ nm [1]. Recently, AlGaAs quantum well laser diodes with graded index waveguides obtained by this technique were also reported [2]. An item of major concern for all diode laser is the temperature dependence of the threshold current density. This is particularly important because in practical applications the heat-sink temperature often becomes much higher than room temperature, and it is necessary for the laser to be operated stable even at such high temperature. In this work, the temperature dependence of the threshold current density is theoretical and experimentally analyzed for lasers with active layer thicknesses of 12 and 30 nm respectively grown by LT-LPE. Three loss mechanisms: the leakage current, the nonradiative recombination in the L and X conduction band minima and the Auger recombination are taken into account to explain the increase of J_{th} with temperature observed experimentally. It will be shown that our experimental results fit quite well with the theoretical predictions and that the mayor influence factor in the behavior of the threshold current density temperature dependence is the leakage current, which become important over room temperature.

2. Device details

The devices used in the present study were straight separate confinement heterostructure (SCH) five layers $Al_xGa_{1-x}As$ laser diodes in the stripe metal contact configuration. Two structures are analyzed, the conventional one with active layer thickness of 30 nm and the QW structure with an active layer thickness of 12 nm. The Al content x for $Al_xGa_{1-x}As$ in the active, barrier and cladding layers are 0.14, 0.34 and 0.7, respectively, in the conventional structure; and 0.03, 0.28 and 0.7 in the QW structure. The aluminum composition of these layers was determined using the double crystal X-ray diffractometry and Raman measurements as was reported previously [3]. Details of the growth procedures and about the heterostructures are given elsewhere [1,4]. For the experiments, as cleaved laser diodes were mounted on a copper heat-sink in which a thermocouple was embedded. The temperature was varied from 77 to 350 K. The device measurements were carried out in pulse mode with a pulse length of 1 μs and a repetition rate of 1 Khz. The threshold current is obtained from the light-current characteristic.

3. Calculations of the threshold current density

In order to explain the experimental temperature dependence of the threshold current, some loss mechanisms must be taken into account. In this work, following Ref. [5] we consider three such mechanisms that contribute to an excess of nonradiative current density:

nonradiative recombination in the L and X conduction band minima, nonradiative Auger recombination and the leakage of carriers across the heterobarriers.

3.1. Radiative current

The radiative component to the threshold current density is

$$J_{\mathrm{rad}} = J_0 + \frac{d\Gamma}{\eta_{\mathrm{i}}\beta}\left[\alpha_{\mathrm{i}} + \frac{1}{L}\ln\left(\frac{1}{R}\right)\right], \tag{1}$$

where, d is the active layer thickness, L is the cavity length and R is the mirror reflectivity. The internal quantum efficiency η_{i} is taken equal to the unity and the intrinsic loss α_{i}, is obtained from the measured length dependence of the differential quantum efficiency. For α_{i} we found, in the conventional structure 7.6 cm^{-1} and in the QW structure 20 cm^{-1}. The confinement factor Γ was calculated from electromagnetic wave analysis and results to be 0.12 for the conventional structure and 0.042 for the QW structure. In this work we considered the thermal dependence of the gain coefficient β through the simulated relation: $\beta = 9.3311\,T^{0.913}$ that was obtained based in a previous reported data [6]. The threshold current density at transparency J_0 can be evaluated as follows

$$J_0 = \frac{n_0 e d}{\tau}, \tag{2}$$

where d is 30 nm and 12 nm for the two structures compared, τ is the radiative lifetime taken as 2 ns and n_0, the injected carrier density needed for transparency, can be derived from the laser threshold condition

$$E_{\mathrm{F\,e}} + E_{\mathrm{F\,v}} = 0, \tag{3}$$

where $E_{\mathrm{F\,e}}$, $E_{\mathrm{F\,v}}$ are the Fermi energies for the electrons and holes, respectively. They can be obtained using the Joyce and Dixon approximation [7] as follows:

$$\frac{E_{\mathrm{F\,e}}}{kT} = \ln\left(\frac{n}{N_{\mathrm{c}}}\right) + a_1\left(\frac{n}{N_{\mathrm{c}}}\right) + a_2\left(\frac{n}{N_{\mathrm{c}}}\right)^2 + a_3\left(\frac{n}{N_{\mathrm{c}}}\right)^3 + a_4\left(\frac{n}{N_{\mathrm{c}}}\right)^4. \tag{4}$$

For the conventional structure the density of states of the conduction band is $N_{\mathrm{e}} = 2(2\pi m_{\mathrm{e}} kT/h^2)^{3/2}$, the conduction band effective mass $m_{\mathrm{e}} = (0.067 + 0.083\,x)m_0$, $a_1 = 0.35355$, $a_2 = -0.000495$, $a_3 = 1.4838 \times 10^{-4}$ and $a_4 = -4.4256 \times 10^{-6}$. A similar expression holds for $E_{\mathrm{F\,v}}$, with $m_{\mathrm{v}} = (0.48 + 0.31\,x)m_0$. Since in our laser the active layer was not intentionally doped, then from the neutrality condition, $n = p$. In the QW structure the density of states depends linearly with the temperature instead like as $T^{3/2}$ as it does in a bulk material (previous case). Thus the expressions must be changed $N_{(\mathrm{e,v})} = (m_{(\mathrm{c,v})}kT/\pi h^3 d)$. The coefficients are in this case $a_1 = 1/2$, $a_2 = 1/24$, $a_3 = 0$ and $a_4 = -0.000347$.

Considering the temperature dependence of the N_{c} and N_{v}, and using (3) we obtain the n_0 values in the 77–350 K temperature range. The values of n_0 and J_0 obtained in this way are 1.4×10^{18} cm^{-3} and 343 A/cm^2 respectively at 300 K for the conventional structure and 1.1×10^{18} cm^{-3} and 95.9 A/cm^2 for the QW structure at the same temperature.

3.2. Nonradiative currents

The first mechanism considered involves populating the L and X valleys of the conduction band, from which electrons can only recombine with holes through a downward transition involving phonon participation. This additional nonradiative recombination current density is given by

$$J_{\mathrm{nr}}^{L,X} = J_{\mathrm{rad}} \left(\frac{n_L + n_X}{n_\Gamma} \right), \tag{5}$$

where n_L, n_X and n_Γ are the electron concentrations at E_L, E_X and E_Γ conduction band minima respectively and can be easily evaluated from the expressions given in Ref. [8]. This component to the current density results very small in the structures considered in this work because of the small aluminum content in the active layer. It is known that for low Al content the electron concentration in the Γ valley is higher than the concentration in the L or the X valleys. The second mechanism considered is the nonradiative Auger recombination. Although AlGaAs has a lower Auger coefficient C_{A}, in very thin active layer the carrier concentrations requirements are higher than in the normal case and Auger processes may then become important. The additional component to J_{th} due to this process is usually written as

$$J_{\mathrm{Aug}} = edC_{\mathrm{A}} n^3. \tag{6}$$

We used a temperature-dependent Auger coefficient $(C_{\mathrm{A}})_{\mathrm{conv}} = C_{300} \exp[0.0404(T/300)]$ as given in Ref. [9], where $C_{300} = 4.22 \times 10^{-30}$ cm$^6 \cdot$ s^{-1}. At 300 K the additional Auger current density is $J_{\mathrm{Aug}} = 17.4$ A/cm^2 for the conventional structure. For the QW structure $(C_{\mathrm{A}})_{\mathrm{QW}} = (kT/Ea)^{1/2}(C_{\mathrm{A}})_{\mathrm{conv}}$ and J_{Aug} is 33 A/cm^{-2} at room temperature. Notice that the Auger component is greater for the QW structure.

The third and final mechanism considered is the carrier leakage out of the active layer. The leakage current can be evaluated [8] as

$$J_{\mathrm{diff}} = \frac{eDn^+}{L_n \tanh\left(\frac{S}{L_n}\right)}, \tag{7}$$

where L_n and D are the electron diffusion length and the electron diffusion coefficient respectively. We took $L_n = 1$ μm and $D = (kT/e) \cdot \mu_n$ We used $\mu_n = 100$ cm^{2}V/s for a cladding $Al_{0.7}Ga_{0.3}As$ layer. The distance s from the edge of the p-cladding layer to the p-GaAs contact layer is 0.6 and 0.5 μm for the conventional and QW structure respectively. Here, n^+ is the excess electron concentration at the edge of the p-cladding layer and depends on the electron density injected in the active layer. This determines the position of the electron quasi-Fermi level E_{Fc}, assumed to be constant throughout the waveguide layers beyond the edge of the cladding layer. In fact, this means that we

TABLE I. Energy gaps for $Al_xGa_{1-x}As$ as a function of temperature and composition.

Energy gap	Dependence	Range
$E_\Gamma(T,x)$ (eV)	$1.5428 + 1.3182\,x - 4\times10^{-4}(1+0.6\,x)T$	$x < 0.45$
$E_\Gamma(T,x)$ (eV)	$1.5428 + 1.247\,x - 1.147(x-0.45)^2 - 4.2\times10^{-4}T$	$x > 0.45$
$E_x(T,x)$ (eV)	$2.006 + 0.125\,x + 0.143x^2 - 3.6\times10^{-4}T$	whole range
$E_L(T,x)$ (eV)	$1.8654 + 0.642\,x - 5.3\times10^{-4}T$	whole range

are considering a DH instead of the real SC heterostructure. n^+ also depends on the discontinuity of the conduction band ΔE_c. We took a value 0,68/0,32 for the ratio of the conduction to valence band offset according with [10]. The leakage current density $J_{\rm diff}$ in the case of conventional structure at 300 K results in 295 A/cm^2 and for the QW structure $J_{\rm diff} = 72$ A/cm^2.

For computational purposes it is convenient to express the energy gaps as a function of both the temperature and the composition. The dependence of the band gap with temperature was taken from Ref. [11], and that of the energy gaps with the aluminum composition from Ref. [8]. The quantities obtained from these relations are summarized in Table I.

4. DISCUSSION

The individual current components as a function of temperature for both structures is plotted in Fig. 1 showing that over room temperature the most important mechanism is the leakage current in both cases. At a given temperature this loss mechanism also predominates when the Al content in the active layer is increased as reported in our previous paper [1]. The $J_{\rm nr}$ can not be appreciated in the figure because it is very small in comparison with the other components of the total threshold current density.

The total threshold current density $J_{\rm T}$ is the sum of the previous considered current components and can be expressed as

$$J_{\rm T} = J_{\rm rad} + J_{\rm nr} + J_{\rm Aug} + J_{\rm diff}. \tag{8}$$

Figure 2 shows the total current density as a function of temperature evaluated from (8) together with the measured values of $J_{\rm th}$ for a laser diode from the conventional structure. The characteristic temperature T_0 for this device is 123 K and was experimentally obtained using the empirical expression, $J_{\rm th}(T) = J(0)\exp(T/T_0)$ as was previously reported in Ref. [12]. In Fig. 3 the theoretical and experimental values of the threshold current density are plotted for a QW laser. The characteristic temperature T_0 is 200 K for this laser. As can be seen the experimental results fit quite well the theoretical predictions. As demonstrated in the previous calculations, the main mechanism responsible for the increase of $J_{\rm th}$ with the temperature is the leakage current.

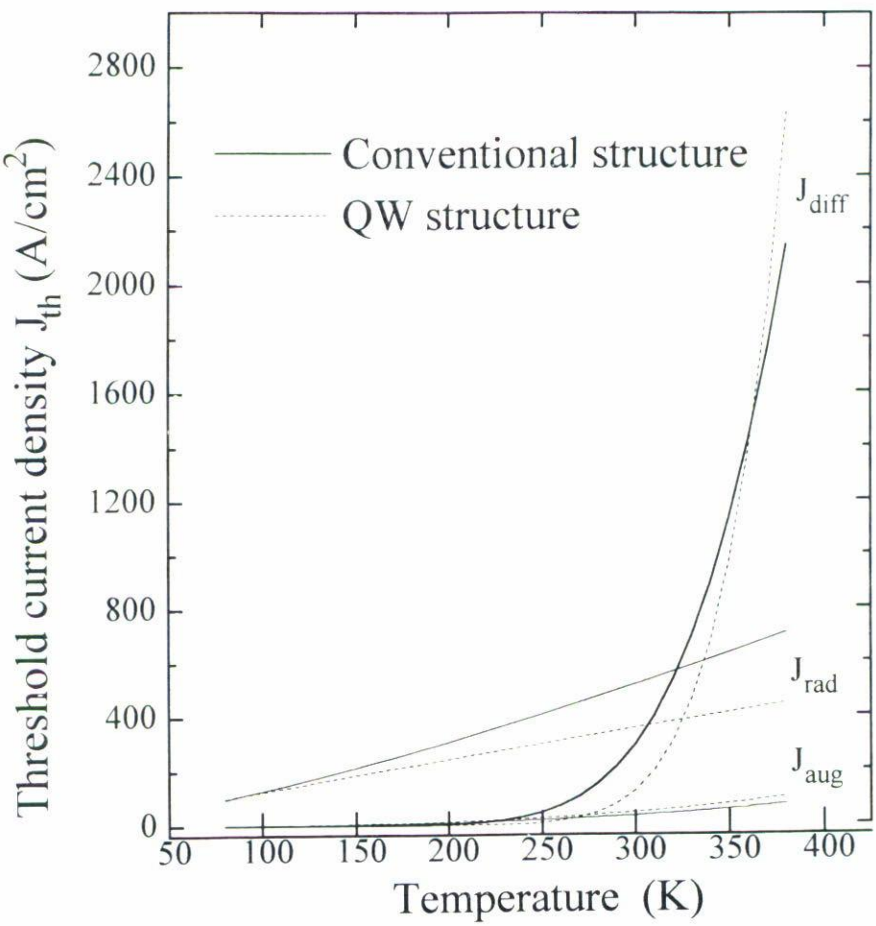

FIGURE 1. Calculated different components of the threshold current density plotted as a function of temperature for the both types of structures studied. The cavity length was taken as 540 μm.

4. CONCLUSIONS

Measurements of J_{th} as a function of temperature are presented for conventional and QW structures grown by LT-LPE. Instead the usual empirical expression for describing the temperature dependence of the threshold current for lasers, we used a theoretical model in which the temperature dependence of all the involved parameters, including the gain coefficient β was considered. The measurements are reproduced by this model. Moreover, it is demonstrated that in our lasers the leakage current is the most important thermal loss mechanism responsible for the increasing in J_{th} with temperature. Similar results of the $J_{\mathrm{th}}(T)$ dependence were observed for other laser samples. The relatively high values of T_0 achieved, proves that the LT-LPE technique is useful for the performance of laser diodes with a good thermal stability. The results in the present paper are a contribution to the characterization of laser structures grown by the LT-LPE technique.

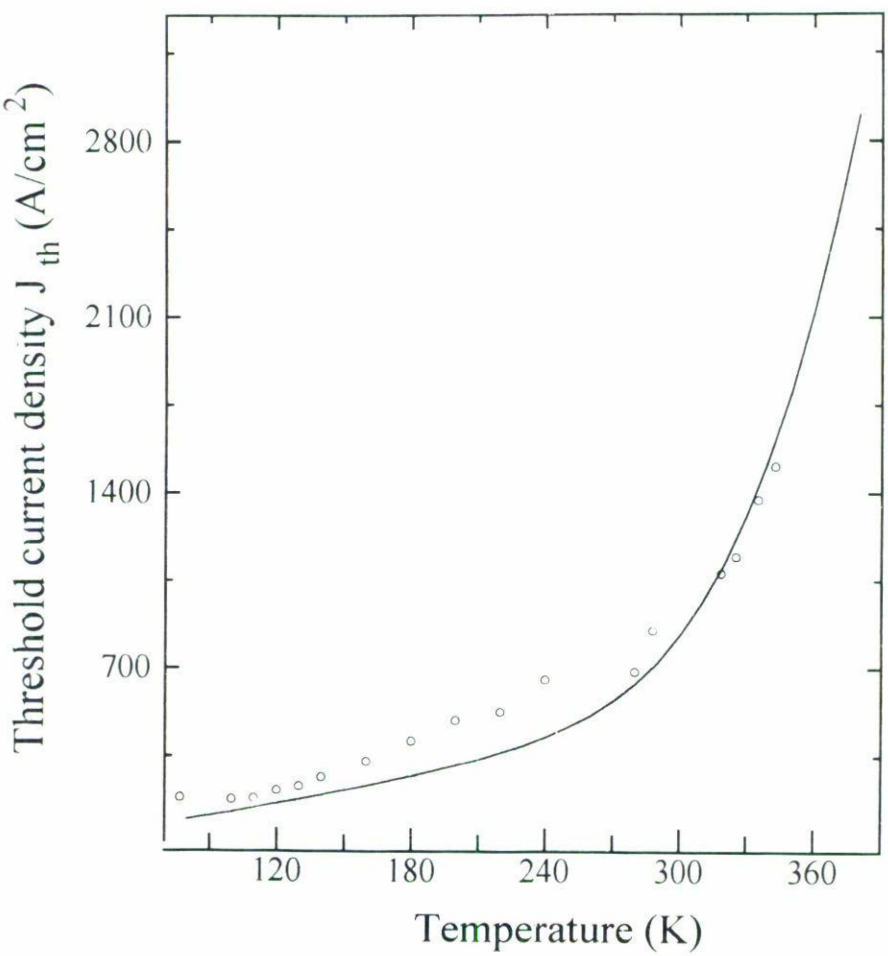

FIGURE 2. Threshold current density as a function of temperature. The open circles are the measured $J_{\rm th}$ for a laser diode with $L = 546$ μm and emission wavelength $\lambda = 756$ nm. The solid curve is the predicted total threshold current density according to expression (8).

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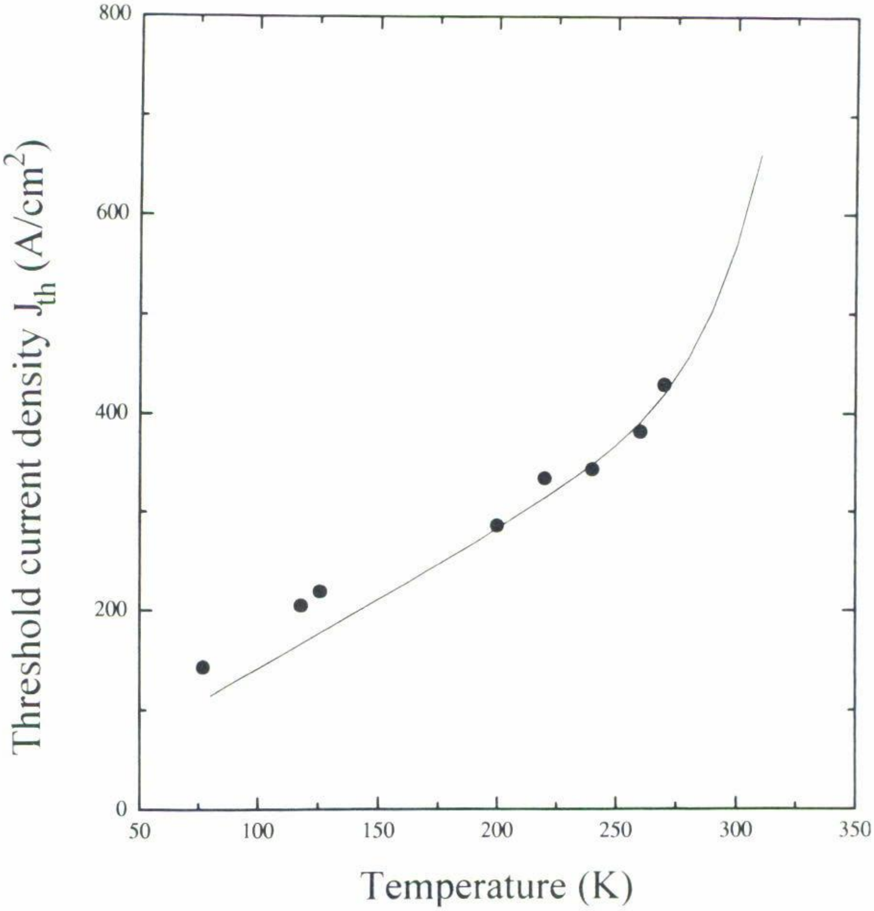

FIGURE 3. Comparison of the measured and calculated threshold current as a function of temperature for a QW laser with cavity length $L = 420$ μm and emission wavelength $\lambda = 830$ nm.

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