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(Laser, Atomic and Molecular Physics)

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ABSTRACT

The effect of nonradiative Auger and Shockley-Hall-Read recombinations and nonlinear gain on InGaAsP/InP ($\lambda = 1.3\ \mu m$) DHS and QW laser transient process and threshold parameters has been studied on the basis of numerical solving the rate equations of a laser. Temperature dependence of a threshold current of InGaAsP/InP ($\lambda = 1.3\ \mu m$) laser has been analysed using real values of the laser diode cavity parameters.

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Preface

The ICTP-LAMP reports consist of manuscripts relevant to seminars and discussions held at ICTP in the field of Laser, Atomic and Molecular Physics (LAMP).

These reports aim at informing LAMP researchers on the activity carried out at ICTP in their field of interest, with the specific purpose of stimulating scientific contacts and collaboration of physicists from Third World Countries.

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I. INTRODUCTION

At the present time transient processes in semiconductor double heterostructure (DHS) lasers and lasers with quantum well (QW) layers are investigated intensively. It is caused by the necessity to control properties and parameters of laser operation in different regimes and conditions, such as turning on/off, switching, regimes of high-speed modulation etc. [1-4].

A distinguishing feature of a laser transient process after turning on an injection current is the oscillating behaviour of output intensity and carrier concentration which relax to a steady-state point in some oscillation cycles [2,3]. Also transient process is characterised by a temporal delay of the first output peak. Its value may vary from ≈0.5 ns to 10 ns. Delay time, amplitude of relaxation oscillation , frequency and a number of oscillations, and relaxation damping rate depend a lot on the parameters determined by properties of semiconductor materials and laser structure, and by features of radiative and nonradiative recombination, relaxation processes, injection conditions, and temperature as well. Transient processes are thought to depend in the most on gain and its nonlinearity. Many other parameters such as photon nonradiative-life time, internal losses, and spontaneous recombination rate are usually considered as being of minor importance. Such separation on main and second-grade factors is valid for steady-state laser regimes [5-7]. But in nonstationar conditions time of an injection current switching on may be comparable to or less than that of nonradiative recombination. In this case nonradiative recombination influences laser output dynamics as significantly as gain does.

In this work we present the investigation and modelling of influence of nonradiative Auger and Shockley-Hall-Read (SHR) recombinations, nonlinear gain, and internal losses on a DHS and QW laser transient process. A nonradiative recombination contribution to the delay time dependence on injection current is considered; temperature dependence of threshold current is calculated taking into account temperature characteristics of Auger recombination, internal losses, spontaneous recombination and gain; the influence of Auger and SHR recombinations on a threshold current is studied as well. Temperature dependence of a threshold current of InGaAsP/InP (λ=1.3 μm) laser has been analysed using real values of the laser diode cavity parameters.

II. TRANSIENT PROCESS, EQUATIONS AND PARAMETERS

Rate equations for photon density q and carrier concentration n are of the form

$$\frac{dn}{dt} = \frac{j}{ed} - An(N+n) - Gv_g q - R_{Auger} - R_{SHR}, \qquad (1)$$

$$\frac{dq}{dt} = \Gamma G v_g q - q/\tau_{ph} + \gamma R_{sp}, \qquad (2)$$

where N is the doping concentration in an active layer ($N \approx 10^{23}$ m^{-3}), j is the injection current density, d is the active layer thickness, A is the spontaneous recombination coefficient, v_g is the group velocity of light in a laser structure, G is the gain,

$$G = \frac{g_0(n-n_e)}{1+\varepsilon q}, \qquad (3)$$

g_0 is the differential gain, n_e is the transparency concentration, ε *is the* nonlinear parameter, R_{Auger} is the Auger recombination rate,

$$R_{Auger} = Cnp^2, \qquad (4)$$

p - is the hole concentration, R_{SHR} - is the SHR recombination rate,

$$R_{shr} = \frac{np}{\tau_n n + \tau_p p}, \qquad (5)$$

τ_n and τ_p are temporal parameters of SHR recombination, Γ is the confinement factor, $\tau_{ph} = 1/v_g\alpha$, $\alpha=\alpha_{int}+\alpha_m$, α_{int} is internal cavity losses, α_m is mirror losses, γR_{sp} represents the spontaneous recombination contribution into laser mode.

Laser transient processes are investigated on the basis of numerical solving Eqs. (1-2) for DHS and tensile strained QW

InGaAsP/InP (λ=1.3 μm) lasers. Auger coefficient C varies from 10^{-42} m^6/s to $6{\cdot}10^{-41}$ m^6/s [5-7]. For the SHR recombination we choose $\tau_n = \tau_p = \tau_{SHR}$ from 10 ns to 90 ns [5-7].

III. RESULTS AND DISCUSSION

Transient process characteristics. The temporal behaviour of photon density and carrier concentration have been studied for the lasers with the following parameters (T=300 K):

DHS:

A	=	$2.8{\cdot}10^{-16}$ m^3/S	[3]
C	=	$2.7{\cdot}10^{-41}$ m^6/S	[8,9]
g_0	=	$2.4{\cdot}10^{-20}$ m^2	[10]
n_e	=	$1.2{\cdot}10^{24}$ m^{-3}	[10]
ε	=	$3{\cdot}10^{-23}$ m^3	[11]
α	=	5500 m^{-1}	[12]
Γ	=	0.4	
d	=	0.2 μm	
n	=	3.5	

QW:

A	=	$2.8{\cdot}10^{-16}$ m^3/S	[3,13]
C	=	$2.0{\cdot}10^{-42}$ m^6/S	[9]
g_0	=	$16{\cdot}10^{-20}$ m^2	[14]
n_e	=	$1.6{\cdot}10^{24}$ m^{-3}	[14]
ε	=	$3{\cdot}10^{-23}$ m^3	[11]
α	=	5500 m^{-1}	
Γ	=	0.05	
d	=	0.01 μm	
n	=	3.5	

In Fig.1 we show a transient relaxation of a DHS laser output. When nonradiative Auger and SHR recombinations are negligible (C =0, $\tau_{SHR} = \infty$) the laser output oscillates a lot before reaching the steady-state point. When nonradiative recombinations effect the lasing process significantly (C =$27{\cdot}10^{-42}$ m^6/s and τ_{SHR} = 10 ns) q dependence on t has got only few oscillation cycles and their damping rates increase. This increase in damping rate is similar to that one caused by a nonlinear part of a gain [3]. So, in transient processes influence of gain nonlinearity and nonradiative recombination on an output dynamics has to be considered as being of equal importance.

Moreover, in the right hand part of Eq.(1) a nonlinear part of a gain is smaller than R_{Auger} when $j<j_{th}$, and they are approximately the same when $j>>j_{th}$.

Nonradiative recombination causes the delay time to rise. An increase in τ_{del} is very large for $j\leq 2j_{th}$ and is not significant for $j\geq 5j_{th}$. The dependence τ_{del} on injection current is shown in Fig. 2. As is seen nonradiative SHR recombination may increase the delay time drastically. At the same time, in a steady-state regime Auger and SHR recombinations change output intensity and carrier concentration slightly (see right side of lines in Fig.1). It corresponds to results of laser simulation [5-7].

In Fig. 3 it is shown that τ_{del} of DHS and QW lasers is almost linearly dependent on $\ln\{j/(j-j_{th})\}$. Such behaviour of the delay time corresponds very well to previously known theoretical results [4]. Only for large currents can we observe a slight deviation from linearity. Let's notice that for DHS and QW lasers slopes of τ_{del} dependencies are equal but for QW laser this value is smaller than that for DHS one. This is one more advantage of QW lasers.

Threshold current. This parameter may depend to a considerable extent on nonradiative recombination characteristics and their temperature behaviour. Auger coefficient C for different laser structures may vary in a widely from 10^{-42} m^6/s to $6{\cdot}10^{-40}$ m^6/s [8,9,11]. It is shown in Fig.4 that threshold currents of DHS and QW lasers depend on C linearly, and QW-slope is a little bit larger than a DHS one (j_{th0} is J_{th} at C =10^{-41} m^6/s for DHS and at C =$0.93{\cdot}10^{-42}$ m^6/s for QW respectively). Also in the case of SHR recombination τ_{SHR} may vary from 4 ns to 100 ns [5-7]. Normalised threshold current dependence on τ_{SHR} is nonlinear. It is represented in Fig. 5. This dependence becomes very sharp when SHR recombination is significant (τ_{SHR}<20 ns). As is seen from Fig.5 dependences of a threshold carrents on τ_{SHR} for DHS and QW lasers differ a little from each other.

Parameters of physical processes responsible for a laser operation consequently change with the change in temperature. An increase in temperature effects a spontaneous emission rate A [15], differential gain g_0 [16], transparency concentration n_e [16], Auger coefficient C [8,15], internal losses α_{int} [12] which in their turn influence on a threshold current. The dependence of j_{th} on T is shown in Fig.6. It is nonlinear and sharp. This result corresponds to experimental data (temperature sensitivity parameter - $T_0 \approx 110$ K, current leakage is not taken into account [17]). For comparison Fig.6 contains curves (1-5) for which only one from the mentioned parameters is temperature dependent.

IV. CONCLUSION

The effect of nonradiative Auger and Shockley-Hall-Read recombinations on a transient process of DHS and QW InGaAsP/InP (λ=1.3 μm) laser switching on and threshold parameters has been studied. It is shown that nonradiative recombinations increase the relaxation recombination damping rate and significantly decrease an oscillation cycle number . Delay time dependence on nonradiative recombination parameters and injection current is calculated on the basis of numerical solving for photon density and carrier concentration rate equations. Results corroborate previous theoretical prediction of linear τ_{del} - $\ln\{j/(j-j_{th})\}$ dependence. Threshold current undergoes linear rise with Auger coefficient C increasing. Threshold current dependence on Shockley-Hall-Read nonradiative recombination parameter τ_{SHR} is nonlinear and rather sharp for τ_{SHR}<20 ns. Temperature influence on a threshold current is calculated in 250÷310K temperature interval for DHS laser. Temperature dependence of spontaneous emission rate, differential gain, transparency concentration, Auger recombination and internal losses is taken into account. Temperature sensitivity parameter T_0 in threshold current dependence $j_{th}(T)\sim j_0\exp(T/T_0)$ is approximately 110K and corresponds to experimental data.

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FIGURE CAPTIONS

Fig.1 Time evolution of photon density and carrier concentration:
1 - C=27·10^{-42} m^6/s, τ_{SHR}=10 ns;
2 - C=27·10^{-42} m^6/s, τ_{SHR}=50 ns;
3 - C=27·10^{-42} m^6/s, τ_{SHR}=1 s;
4 - C=0, τ_{SHR}=1 s.

Fig.2 Delay time dependence on injection current density:
1 - C=27·10^{-42} m^6/s, τ_{SHR}=10 ns;
2 - C=27·10^{-42} m^6/s, τ_{SHR}=50 ns;
3 - C=27·10^{-42} m^6/s, τ_{SHR}=1 s;
4 - C=0, τ_{SHR}=1 s.

Fig.3 Delay time versus $\ln\{j/(j-j_{th})\}$.

Fig.4 Normalised threshold current density as a function of Auger coefficient.

Fig.5 Normalised threshold current density dependence on SHR recombination parameter τ_{SHR}.

Fig.6 Normalised threshold current density versus temperature:
1 - A is $A(T)$;
2 - C is $C(T)$;
3 - α is $\alpha(T)$;
4 - g_0 is $g_0(T)$;
5 - n_0 is $n_0(T)$;
6 - total dependece on T.

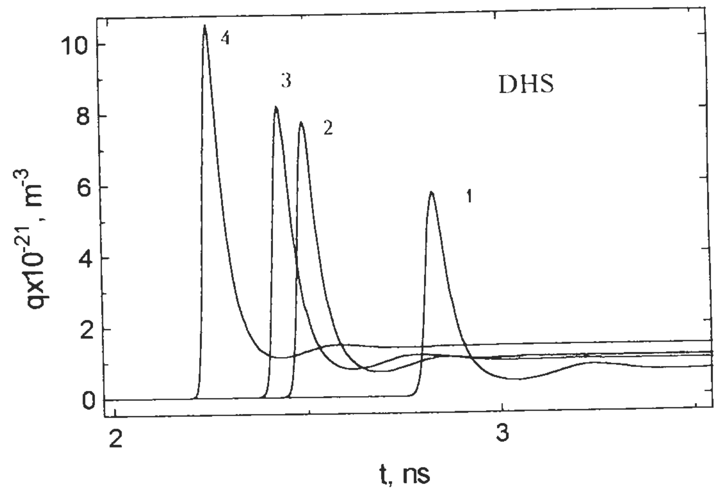


Figure 1a.

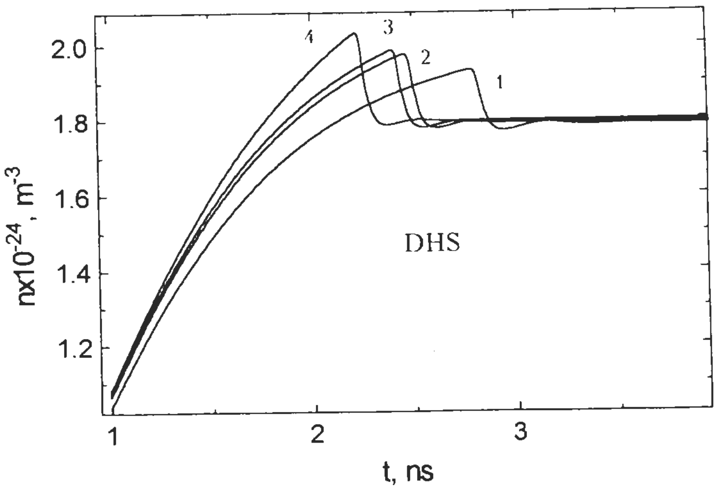
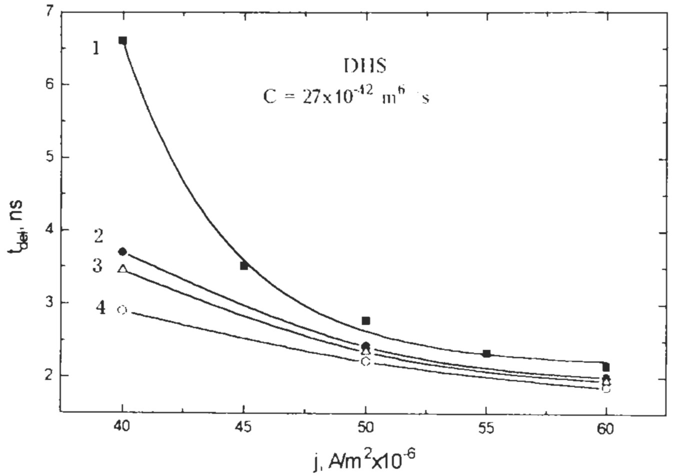


Figure 1b.



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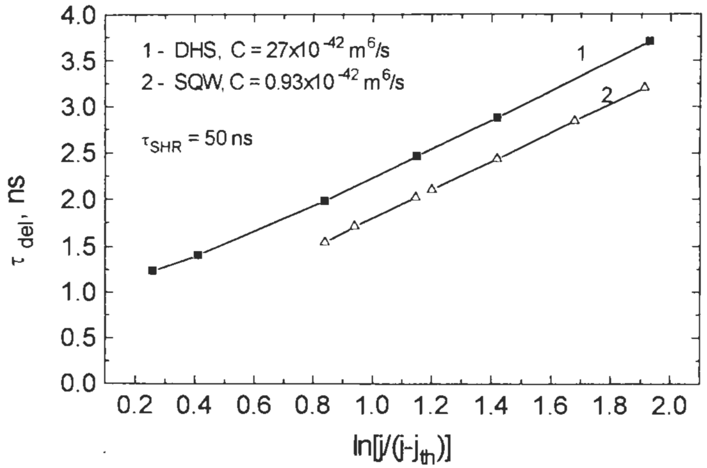
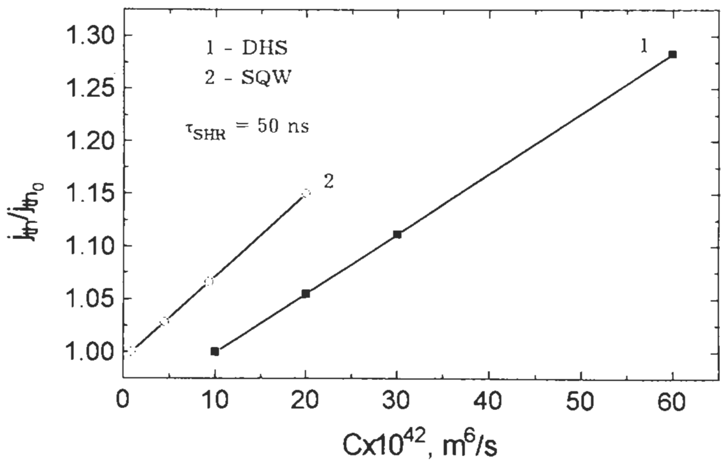


Figure 3.



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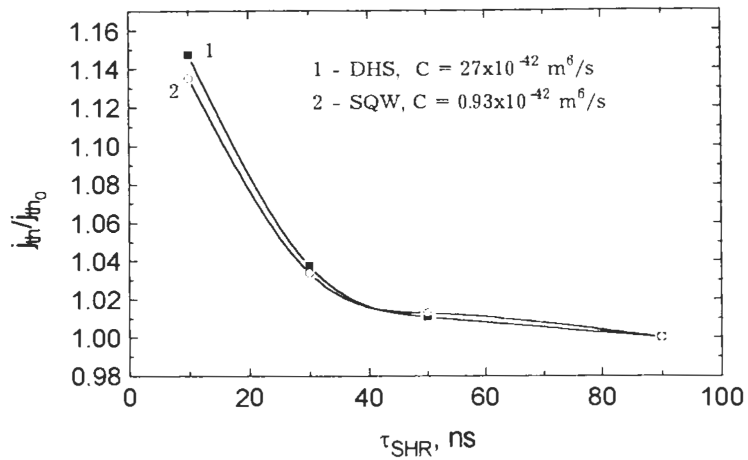

Figure 5.

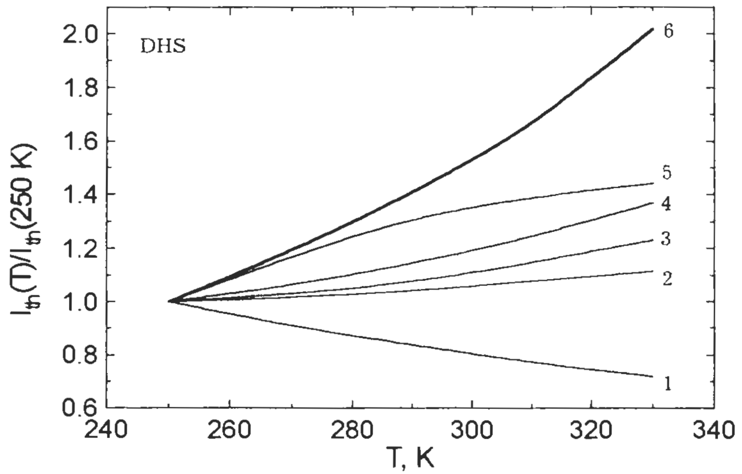

Figure 6.