Temperature-dependent measurement of Auger recombination in self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots

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(Received 16 April 2001; accepted for publication 18 June 2001)

We report experimental studies of temperature-dependent Auger recombination coefficients in self-assembled quantum dots. The results are based on a study of temperature-dependent large signal modulation experiments made on self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dot lasers. The Auger coefficient *decreases* from $\sim 8\times 10^{-29}$ cm^6/s at 100 K to $\sim 4\times 10^{-29}$ cm^6/s at 300 K. This behavior, which is different from results in other higher-dimensional systems, is explained in terms of the temperature dependence of electron-hole scattering in the dots and contribution from higher lying states in the dot and adjoining layers.
[DOI: 10.1063/1.1391401]

Self-organized In(Ga)As/Ga(Al)As quantum dot interband lasers have been studied and characterized extensively over the past few years. Low threshold current, large modulation bandwidth, and low chirp and linewidth enhancement factor, which are essential for optical communication systems, have been demonstrated in these devices.[1–6] Auger recombination in small-band gap materials affects the performance characteristics of lasers adversely, by increasing the threshold current and damping, and reducing the modulation bandwidth. An elegant technique to determine the nonradiative Auger recombination rates and Auger coefficients is the measurement of the turn-on delay of a laser resulting from a large signal current pulse or large signal modulation. The turn-on dynamics of quantum dot lasers have been theoretically investigated by Grundmann.[7,8] But there has been no experimental report on the measurement of Auger coefficients. In this letter we report the measurement of the turn-on delay of $In_{0.4}Ga_{0.6}As/GaAs$ quantum dot lasers and the Auger coefficients in the dots.

To understand the difference in the Auger process in quasi-zero-dimensional systems and quantum well systems (or bulk semiconductors) it is important to note two key issues with reference to Fig. 1(a): (i) the low lying electron states in quantum dot systems are discrete in contrast to other systems; (ii) occupation of the low lying electron states depends strongly on electron-hole scattering and on hole occupation of the ground state. The higher energy states needed for the final state in Auger process are in a continuum as in quantum well or bulk systems. We find that temperature dependence of the measured Auger coefficient can be understood in terms of the two issues mentioned earlier.

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The basis for the determination of the Auger coefficients is the carrier rate equation below threshold

$$\frac{dn}{dt}=\frac{I}{qV}-R(n), \tag{1}$$

where, in general, the total recombination rate $R(n)$ is expressed as

$$R(n)=\frac{n}{\tau}=A_{\rm nr}n+R_{\rm sp}n^2+C_a n^3 \tag{2}$$

in terms of the effective carrier lifetime τ, the Shockley–Read–Hall coefficient $A_{\rm nr}$, the radiative recombination coefficient $R_{\rm sp}$, the carrier density n, and the Auger coefficient C_a. Integration of Eq. (1) with appropriate boundary values yields the expression for the turn-on delay time

$$\tau_d=qV\int_0^{n_{\rm th}}\frac{1}{I-qVR(n)}\,dn, \tag{3}$$

where V is the active volume. Therefore, measurement of the stimulated emission delay times and calculation of the radiative recombination rates and the threshold carrier density allow an accurate determination of the Auger coefficient in a self-consistent manner.[9] In our experiment we have extended this technique to the measurement of C_a, as a function of temperature, in the active region of $In_{0.4}Ga_{0.6}As/GaAs$ quantum dot lasers. Shockley–Read–Hall recombination at traps and defects has been neglected in the current analysis of the data, based on the following experimental observations: (a) the density of nonradiative trap states arising from point defects in and around the dots are an order of magnitude smaller than typical dot densities,[10] (b) no Stokes shift of the photoluminescence is detected;[11,12] and (c) defect related nonradiative recombination associated with ground state transition is negligible.[13,14]

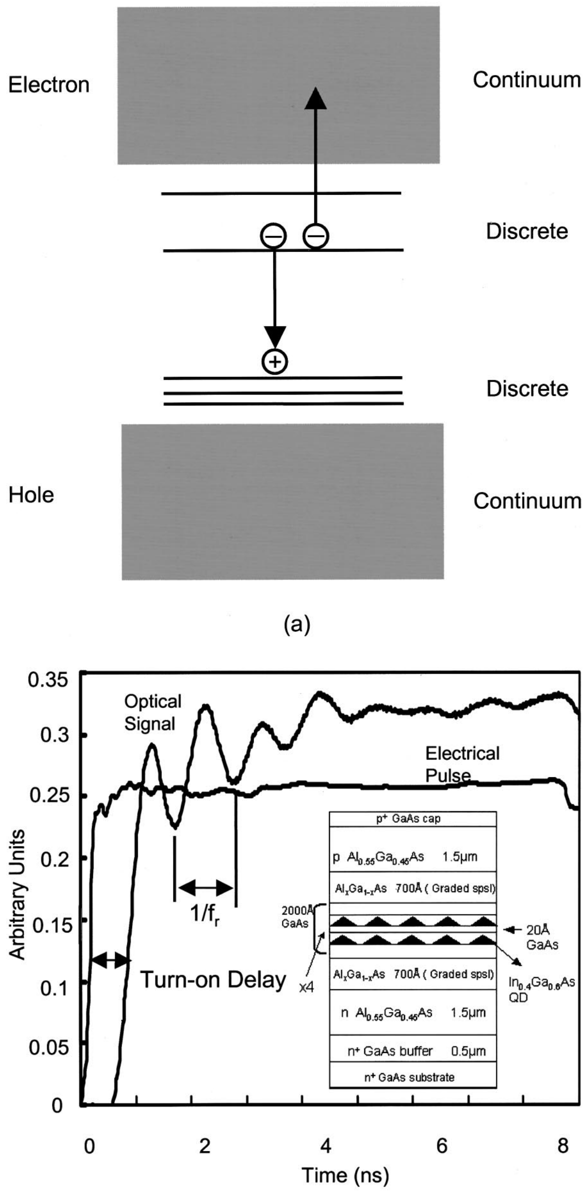

FIG. 1. (a) A schematic of the Auger transition in a quantum dot system. Hole occupation of the ground state is critical for the process to occur; (b) temporal characteristics of the pulsed bias current and the output optical pulse. The delay time is measured between the 50% points. The inset shows the quantum dot laser heterostructure grown by molecular beam epitaxy.

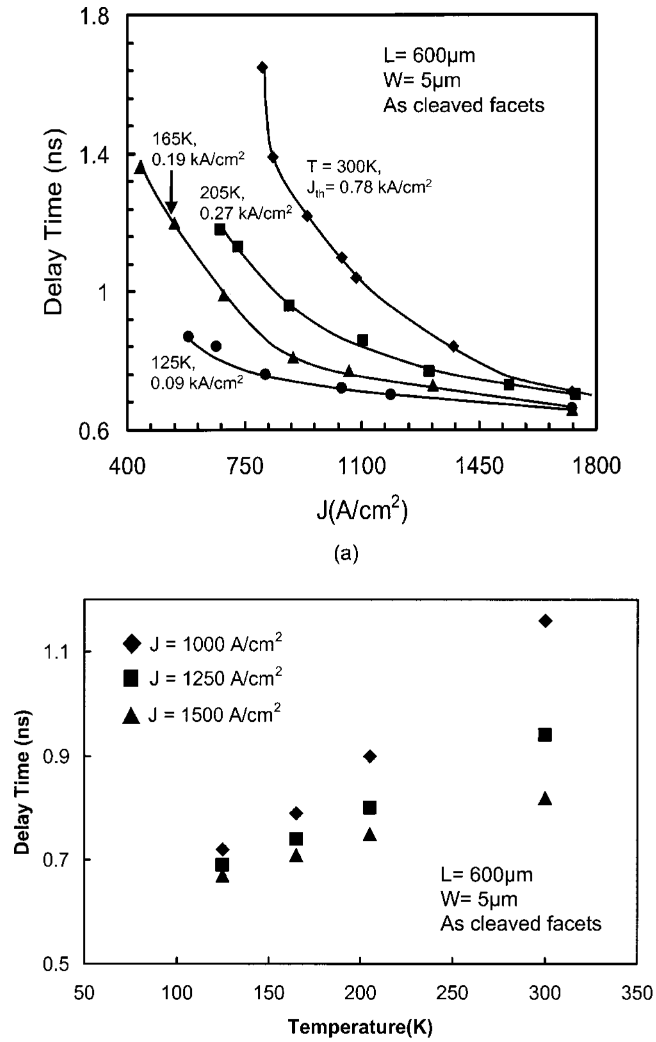

FIG. 2. (a) Measured turn-on delay times as a function of injection current density at different temperatures. The solid curves are joins of the data points; (b) measured delay times as a function of temperature for fixed injection current densities.

The $In_{0.4}Ga_{0.6}As/GaAs$ self-organized quantum dot separate confinement heterostructure lasers were grown by solid source molecular beam epitaxy; the layer structure is shown in the inset of Fig. 1. Single-mode ridge waveguide lasers with ridge widths 3, 5, 8, and length 600 μm were fabricated by standard photolithography and lift-off techniques and a combination of wet and dry etching. The lasing wavelength is measured to be 1.04 μm at room temperature and the threshold currents are in the range 15–50 mA for different ridge widths. Large-signal modulation measurements were done at room temperature and lower temperatures in a closed cycle helium cryostat with feedthrough microwave probes and optical fiber. The lasers were pulse biased with a 10% duty cycle from $I=0$ to $I(>I_{th})$ with 100 ps (20%–80%) rise time electrical pulses. The output is detected with a 40 GHz InGaAs photodetector. The delay time between the electrical and optical signal is measured with a high-speed digital sampling oscilloscope, taking into account the delays due to the optical fiber, rf cables, the photodetector and low noise amplifier.

Figure 1(b) illustrates the typical temporal characteristics of the bias current pulse and the output optical pulse, with the characteristic relaxation oscillations (RO) in the latter. Figure 2(a) shows the experimentally determined turn-on delay times as a function of bias current density at different ambient temperatures. The delay times decrease with increasing current since the higher injected carrier density reduces the recombination lifetime.

To determine the Auger coefficients, the gain and spontaneous recombination rates are calculated using the Fermi golden rule with a eight-band $\mathbf{k}\cdot\mathbf{p}$ description[15] of the bands and n_{th} is determined with a measured value of cavity loss (2.7 cm^{-1}) using multimode coupled rate equations. It is important to note that in order to represent the carrier dynamics in the quantum dot heterostructure more accurately, the carrier distribution in the wetting layers and barrier layers have also to be taken into account. An optical confinement factor

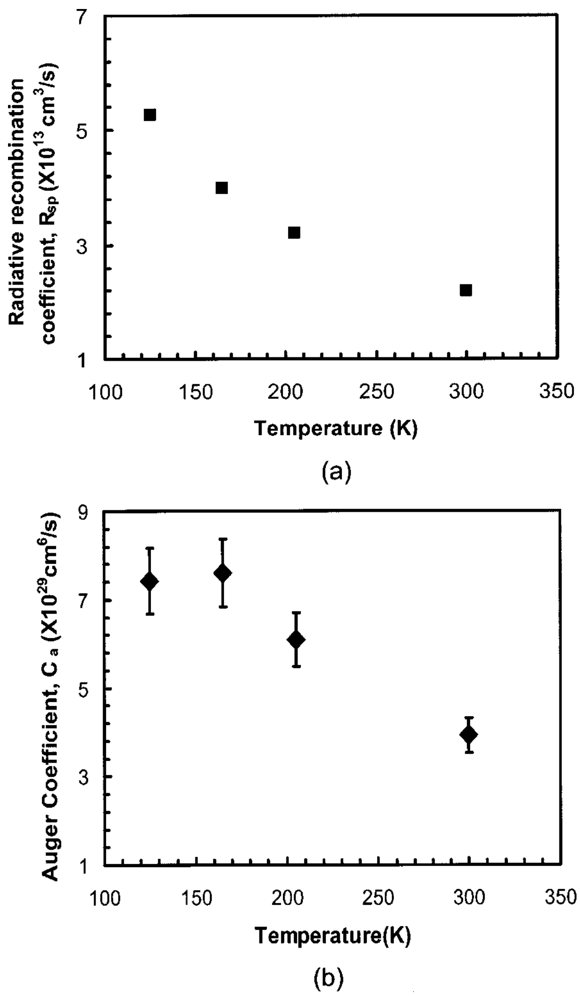

FIG. 3. (a) The variation of the calculated radiative recombination coefficient with temperature is shown. (b) Variation of the Auger recombination coefficient with temperature.

of 0.012 is calculated for the lasers studied. The multimode coupled rate equations are solved at different temperatures using the fourth order Runge–Kutta technique and time evolution of the photon density is used to extract the theoretical delay time. The inhomogeneous broadening in the quantum dots is varied such that the experimental and calculated J_{th} are matched at each temperature. The Auger coefficient C_a is obtained by minimizing the root mean square error between the theoretical and experimental delay times. The variation of R_{sp} and C_a with temperature are shown in Figs. 3(a) and 3(b), respectively. The most striking results are the large increase of the delay time and the decrease of the Auger coefficient with increase of temperature. In bulk and quantum well materials, only a very small temperature dependence (increase with temperature) of τ_d has been observed, while C_a is known to increase with increase in temperature. Also significant is the decrease of the value of R_{sp} with increase in temperature.

The electron-hole scattering mechanism has been identified by us and others to be a dominant scattering mechanism via which hot electron relaxation takes place in quantum dots.[16–20] The electrons in the ground state can then participate in the Auger process as depicted in Fig. 1(a). Due to the nature of the valence band states, the levels in the valence band are separated by energies smaller than the optical phonon energy. This allows holes to thermalize rapidly. Hot electrons in the excited conduction band levels can scatter from these cold holes and transfer their energy. The holes then lose the excess energy via phonons.

At cryogenic temperatures, the calculated and measured relaxation times of electrons from the excited states to the ground states are ~8 ps.[18] With increase of temperature, the thermal excitation of holes from the lowest quantum dot levels will decrease the rate of this process, since there are fewer holes for the electrons to recombine with. Indeed, an increase in the electron relaxation time with temperature has been measured.[19] An increase in quantum dot luminescence relaxation time with increasing temperature, agreeing with our results, has been measured by Brasken *et al.*,[20] which is also explained in terms of the electron-hole scattering process. We believe that the observed increase in turn-on delay time and decrease in the Auger recombination coefficient, C_a, with increasing temperature is a direct consequence of the temperature dependence of the ground state hole occupation, which in turn controls the rate of electron-hole scattering.

The work is being supported the National Science Foundation under Grant No. ECS 9820129 and the Army Research Office (MURI program) under Grant No. DAAD 19-99-1-0198.

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