Charge-Carrier Concentration and Temperature in Quantum Wells of Laser Heterostructures under Spontaneous- and Stimulated-Emission Conditions


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Abstract—The charge-carrier concentration and the temperature of hot electrons and holes in quantum-well laser nanostructures in the regimes of spontaneous and stimulated emission are determined as functions of the current density $j$, with InGaAs/GaAs structures as an example. Under spontaneous-emission conditions, the carrier concentration in the active region of a laser structure grows as the current increases, while carrier heating is insignificant. The spontaneous-emission spectra calculated taking into account forbidden optical transitions agree well with the experimental ones. Under stimulated-emission conditions, the behavior is quite different. When the pump current density is comparatively low (several times above the threshold), the concentration of injected charge carriers levels off and does not grow as the current increases, while the carrier temperature rises considerably. When the current density exceeds the threshold value by orders of magnitude, stabilization of the charge-carrier concentration does not take place; the carrier concentration exhibits a severalfold increase and the carrier temperature rises to about 450 K at $j = 80$ kA/cm$^2$. The number of the charge carriers escaping from the quantum wells into the barriers, which determines the laser efficiency, also increases under these conditions because of the carrier heating. This undesirable effect can be weakened by increasing the depth of the quantum wells.

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1. INTRODUCTION

It is well known that the concentration of injected charge carriers $n$ in laser heterostructures with quantum wells (QWs) increases as the current density $j$ is raised. The variation in $n$, as a function of $j$ is mainly determined by the following three processes: nonradiative recombination via traps, radiative bimolecular recombination, and Auger recombination. After the threshold current $j_{th}$ is reached, the $n(j)$ dependence levels off: as the current increases still further, the charge-carrier concentration in the QWs remains unchanged due to a reduction in the carrier radiative lifetime $\tau(j)$ caused by the stimulated photon emission. The probability of the photon emission is proportional to the number of photons $n^{(\nu)}$, which, for $j > j_{th}$, is proportional to the current density: $n^{(\nu)} \propto j$. In this situation, $\tau^{(\nu)} \propto j^{-1}$. Stabilization of the carrier concentration $n$, under lasing conditions can be recognized experimentally by the dependence of the intersubband absorption of the radiation in the middle infrared (IR) range on the current density $j$. Saturation of the intersubband absorption in the near-IR range with increasing optical-excitation level above the laser-oscillation threshold was observed, e.g., in [1, 2].

However, under high levels of electrical or optical injection of electrons and holes, their heating is possible. Typically, the threshold value of the electron and hole concentrations corresponding to the onset of laser oscillation at $T = 300$ K falls in the range $n = (0.3–3) \times 10^{12}$ cm$^{-2}$, which corresponds to the bulk concentration $n = 2 \times 10^{18}$ cm$^{-3}$. For such high densities, the times of electron–electron ($e-e$), hole–hole ($h-h$), and electron–hole ($e-h$) collisions are shorter than the optical-phonon emission time. Consequently, the excess energy of charge carriers injected into the continuum is transferred to the carriers in the lower quantum-confinement subbands in the QWs via $e-e$, $h-h$, and $e-h$ collisions, which causes carrier heating. This process may become especially significant in the above-threshold conditions, since the carrier concentration does not grow or grows very slowly with increasing the injection level, while the energy flux (i.e., the energy increase rate) per charge carrier increases as the current is raised and may become considerable for $j > j_{th}$. This situation is different from the subthreshold conditions; in the latter case (in the spontaneous-emission conditions),...
$n_i$ increases with $j$ and, thus, the rate of the energy increase per carrier rises much slower with the injection level, provided that the active region is undoped or lightly doped. Possibly, it is for this reason that analysis of the room-temperature electroluminescence (EL) spectra did not reveal heating of the charge carriers in a 1.4-μm-wide undoped active region of laser diodes based on InGaAsP double heterostructures up to the current density $j = 10$ kA/cm$^2$ [3]. Another situation occurs when the EL is observed in a doped active region. Thus, charge-carrier heating in InGaAsP diodes, inferred from the analysis of the EL spectra at $T = 300$ K, was as high as $T_e - T = 400$ K for $j = 25$ kA/cm$^2$ [4] (here, $T_e$ is the electron temperature). A considerable heating of the charge carriers was also revealed in InGaAs/InP/InGaAs heterostructures [5] by means of the analysis of the EL spectra recorded at $T = 300$ and 5 K for the current densities as high as 80 kA/cm$^2$ ($T_e - T$ exceeded 250 K).

Because of the charge-carrier heating at high injection levels in the above-threshold regime, the charge-carrier concentration is expected to grow and stabilization of the concentration to be broken; this fact was noticed in [6]. Heating of the charge carriers results in their escape from the QWs into the barriers; in InGaAs/GaAs QWs under consideration, this effect is especially important for electrons, and in longer wavelength (2.5–2.8 μm) lasers with InGaAsSb/AlGaAsSb QWs, for holes [7, 8]. This process may lead to a reduction in the laser differential efficiency.

Here, we study the above-discussed processes and estimate the concentration of electrons in the QWs and their heating as functions of the current density in injection lasers in the spontaneous- and stimulated-emission conditions.

2. EXPERIMENTAL

Strained asymmetric separate-confinement laser structures with In$_{1-x}$Ga$_x$As/GaAs QWs were grown by metal-organic vapor-phase epitaxy. Properties and characteristics of these lasers were studied previously [9–11]. The band gap $E_g$ and the quantum-confinement energy levels were calculated taking strain into account for a QW of width $L_{QW} = 70$ Å. The energy level diagram at $T = 77$ K is shown in Fig. 1.

For $x = 0.73$, such an In$_{1-x}$Ga$_x$As/GaAs QW has one electron quantum-confinement level ($e_1$), four heavy-hole levels ($hh_1$, $hh_2$, $hh_3$, and $hh_4$), and one light-hole level ($hl_1$). Let $\Delta E_c$ designate the difference between the well depth $\Delta E_e$ and the quantum-confinement energy $E_{e1}$, and $\Delta_{12}$ and $\Delta_{13}$ designate the spacings between the hole energy levels ($\Delta_{12} = E_{hh_2} - E_{hh_1}$, $\Delta_{13} = E_{hh_3} - E_{hh_2}$).

The spectra of the stimulated emission in a laser with the cavity length $L = 1.5$ mm and the stripe width $w = 100$ μm were studied at $T = 300$ K. The threshold current density was equal to $j_{th} = 195$ A/cm$^2$. In order to study the spontaneous-emission regime in a range of current densities as wide as possible, the cavity length