Energy storage in quantum-well lasers

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A new scheme of energy storage in single-quantum-well semiconductor lasers is analyzed. This scheme involves the storage of the majority of injected carriers in the continuum states of the surrounding bulk material, in which the carrier density is diluted and the higher-order carrier-density-dependent recombination processes are much smaller. This allows the inversion level to build up to a much higher level during the pumping stage of Q switching. The possibility of using indirect-band-gap semiconductors for carrier storage is also proposed.

The technique of Q switching is used extensively to obtain intense, short pulses from lasers. The key to high peak power is the energy-storage mechanism of the gain medium, which allows the population inversion to reach a high level during the pumping stage. Q switching is most successfully used in solid-state lasers, such as Nd:YAG lasers, in which the relaxation times of the population inversion range from microseconds to hundreds of microseconds. In semiconductor lasers, Q switching is less efficient owing to the rapid depletion of the inversion by the strong spontaneous emission. For example, the typical carrier lifetime in semiconductor lasers, owing to the spontaneous emission, is of the order of several nanoseconds at threshold. The rate of the spontaneous emission increases with n^2, the square of the carrier density, and becomes a serious energy sink as the carrier density increases. Under higher levels of excitation, other higher-order nonradiative processes such as Auger recombination, proportional to n^3, may also take place.[1] Auger recombination is known to be a strong carrier-depleting mechanism in InGaAsP lasers and was thought to play an important role in single-quantum-well lasers[2–4] in which the threshold carrier density is one order of magnitude higher than in conventional double-heterostructure lasers. In the regime where Auger recombination plays an important role, the inverse of the carrier lifetime, $1/\tau$, increases superlinearly with increasing carrier density.[1] Possible ways of suppressing the spontaneous emission and Auger recombination by creating a photonic band gap[5] or by using band-structure-engineering[6] have also been proposed.

Yablonovitch *et al.*[7] have reported the inhibition and enhancement of the spontaneous emission in semiconductors by controlling the refractive indices of the surrounding media. Recent studies[8] of the differential carrier lifetime[1] in GaAs/AlGaAs and strained-layer InGaAs/GaAs single-quantum-well lasers also reveal that the carrier lifetime is not an intrinsic property of the material but is structure dependent and can be controlled by the height of the potential barrier in a functional laser device. Typically, for a given carrier density, the differential carrier lifetime is longer in quantum wells with lower potential barriers.[8] Under high levels of excitation, the inverse of the differential carrier lifetime increases sublinearly, rather than superlinearly, with increasing carrier density and, in quantum wells with low potential barriers, stays nearly constant, independent of the injected carrier density for $n > 10^{19}/\text{cm}^3$. The commonly used recombination rules for the nonradiative ($\propto n$), bimolecular ($\propto n^2$), and Auger ($\propto n^3$) recombination processes for the bulk material no longer hold. The deviation from the bulk behavior is due to a portion of the injected carriers' populating the continuum states of the thick confinement layers where the carrier volume densities are diluted and thus the n^2 and n^3 recombination rates are much smaller. The lifetime is longer in low-barrier quantum wells because a larger portion of the injected carriers populates the continuum states.[8]

The ability to control the carrier lifetime in a functional semiconductor laser points to the possibility of carrier storage for Q switching. In this Letter we analyze the scheme of energy storage in quantum-well lasers. The method involves the storage of the majority of the injected carriers of a quantum-well laser in the confinement layers that serve as a carrier reservoir. This allows the inversion to build up to a much higher level without being depleted by the fast radiative and nonradiative processes. The storage of carriers also reduces the rate of gain buildup and suppresses the amplified spontaneous emission. To achieve the carrier storage effect, the quantum well must be sufficiently deep to confine enough carriers so that the laser oscillation can still take place at reasonably low

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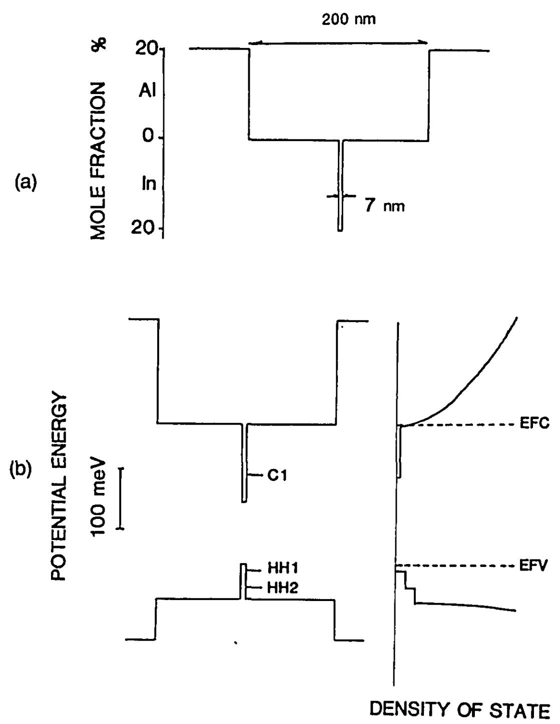

Fig. 1. (a) Layer structure of the InGaAs/GaAs single-quantum-well laser. (b) The potential-energy profile, the density of state, and the confined states of the structure; the dashed lines indicate the quasi-Fermi levels at threshold.

carrier density once the cavity is restored, and the potential barriers must be sufficiently low so that the majority of the excess carriers can populate the continuum states at room temperature.

To demonstrate that the proposed scheme is realistic, we base our analysis on a strained-layer InGaAs/GaAs single-quantum-well laser shown in Fig. 1. This specific structure is selected because the experimental data on threshold gain, carrier density, and carrier lifetime are available and can be used as a reference for the theoretical calculation. However, the principle is also applicable to other quantum-well structures, including AlGaAs/GaAs quantum wells, with similar potential energy profiles. The laser structure consists of a 7-nm-thick strained-layer $In_{0.2}Ga_{0.8}As$ quantum well sandwiched between two 100-nm-thick GaAs confinement layers that are in turn sandwiched between two $Al_{0.2}Ga_{0.8}As$ layers. The device characteristics have been published previously.[8,9] Briefly, the differential carrier lifetime τ is first measured as a function of the injection current I. The injected carrier sheet density n_s is then determined by the relation $n_s = (1/eA) \int \tau(I)dI$, where A is the area of the laser stripe.[1] The carrier density thus determined is $1 \times 10^{13}/cm^2$ at threshold. The modal gain of a 600-μm-long laser device is 22 cm^{-1} at threshold. Here we have expressed the carrier density in terms of the sheet density because the carriers are not necessarily confined in the well. The apparent volume density would be $1.5 \times 10^{19}/cm^3$ at threshold if all the carriers were confined in the quantum well. The experimentally measured $1/\tau$ increases sublinearly with increasing carrier density and stays nearly constant at a $(3\ nsec)^{-1}$ level for $n_s > 0.5 \times 10^{13}/cm^2$.[8] The potential-energy diagram, the density of states, the calculated energy levels of the confined states in the conduction band C1 and in the heavy-hole bands HH1 and HH2, and the quasi-Fermi levels in the conduction band EFC and in the valence band EFV at threshold are shown in Fig. 1(b). The calculation is made based on the material parameters given in Ref. 10. For the strained $In_{0.2}Ga_{0.8}As$ material, we have used an effective mass of 0.058 m_e for the electron, 0.46 m_e for the heavy hole perpendicular to the quantum-well plane, and 0.191 m_e for the heavy hole parallel to the quantum-well plane.[11] The density of state of the confinement layers is approximated by a parabolic-shaped continuum. The light holes are unconfined and therefore are neglected. We have also assumed that, once the cavity is restored, the threshold gain for the Q-switched laser is 22 cm^{-1}.

The carrier storage effect becomes apparent by examining the energy-level and the density-of-state diagrams. The only confined electronic state in the conduction band is located at $\Delta E = 80$ meV ($3\,kT$ for $T = 300$ K) below the edge of the confinement layer. In the limit of low carrier density when the Fermi level is below the band edge, the ratio of the number of carriers per unit energy in the continuum to that in the confined state is estimated to be of the order of 1.[8] Thus even at low carrier densities, a considerable portion of the injected carriers occupies the continuum states. Figure 2 shows the calculated percentage of the injected carriers in the confinement layer as a function of the total injected carrier density. We have found that, for carrier sheet densities above $1 \times 10^{13}/cm^3$, more than 80% of the injected carriers stay in the confinement layers. In this specific example, the ratio of the volume of the quantum well to the volume of the confinement layers is 1/30. Although the total number of carriers in the confinement layers is large, the volume density of the carriers is still in the range of $10^{17}/cm^3$ to $10^{18}/cm^3$, and the radiative and Auger recombination rates, proportional to n^2 and n^3, respectively, are reduced by a factor of 30 and 900, respec-

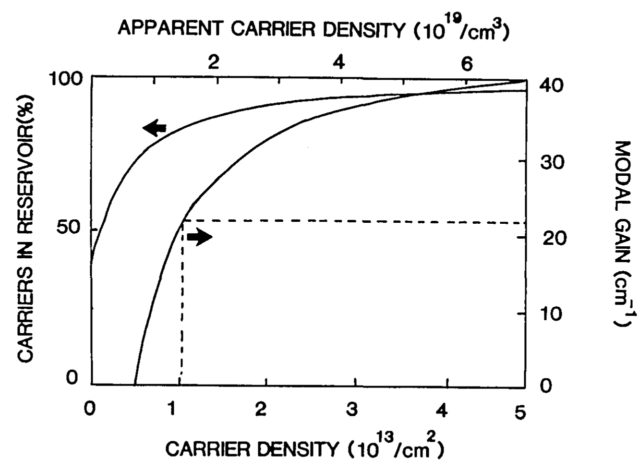

Fig. 2. Calculated peak gain versus carrier density and percentage of the injected carrier in the carrier reservoir. The lower scale shows the injected carrier sheet density, while the upper scale shows the apparent volume density if all the carriers were confined in the well.

tively, when compared with the case if all the carriers were confined in the well. Thus the continuum states serve as a carrier reservoir. The carrier lifetime in the reservoir is primarily limited by the carrier-density-independent nonradiative recombination caused by, e.g., defects and interfacial recombination. In high-quality materials, the recombination rate can be small.

Figure 2 also shows the calculated peak gain at various carrier densities. Owing to lack of detailed knowledge about the magnitude of the radiative transition matrix elements, we first calculated the relative gain based on the energy distribution of the carriers in the conduction band and the valence band and then scaled the magnitudes so that at a carrier density of $n_s = 1 \times 10^{13}/\mathrm{cm}^2$, the modal gain is equal to the experimentally measured threshold gain of 22 cm^{-1}. Since there is only one bound state in the conduction band, the relation of the modal gain versus the carrier density saturates quickly for $n_s > 2 \times 10^{13}/\mathrm{cm}^2$. Above this level, the majority of the injected carriers stay in the reservoir, not contributing to the gain. During the pumping state, the maximum inversion level in conventional semiconductor gain media is limited by carrier depletion caused by the amplified spontaneous emission. Based on the published data on traveling-wave amplifiers,[12] the amplified spontaneous emission becomes a strong carrier-depleting mechanism when the single-pass modal gain reaches 40 dB or when the gain–length product reaches 9.2. For a 600-μm-long gain medium, this corresponds to a modal gain of 150 cm^{-1}. From the rate of gain buildup shown in Fig. 2, it is clear that the modal gain will never reach 150 cm^{-1} and therefore that the amplified spontaneous emission is not a limiting factor for energy storage. Under high levels of excitation, the ultimate limitation of energy storage would be the n^2 and n^3 recombination processes in the reservoir. The carrier storage capacity could be further increased by using an indirect-band-gap semiconductor as the reservoir material. For example, in $Al_xGa_{1-x}As$ with $x > 0.37$, the majority of the carriers populate the indirect valley where the n^2 recombination rate is negligible. The carrier lifetimes in these materials are determined by the nonradiative processes whose lifetimes are independent of n. The feasibility and limitation of this approach require more knowledge about the intervalley scattering rates.

The time of carrier transport from the energy-storage layers into the quantum well through the diffusion process determines the effectiveness of the present scheme for short-pulse generation. In a flat-bottom type of confinement layer, the time to diffuse 100 nm is estimated to be ~20 psec based on a hole diffusion coefficient of 5 cm^2/sec.[13] This is consistent with the measured carrier capture time of less than 20 psec in similar quantum-well structures using picosecond luminescence spectroscopy.[14–16] Thus efficient carrier retrieval is expected for laser pulses longer than the carrier capture time. The use of a graded structure for the confinement layer with a built-in quasi-electric field may further shorten the carrier capture time to 2 psec.[15]

In conclusion, we have analyzed a scheme of energy storage in single-quantum-well semiconductor lasers. This scheme involves the storage of the majority of the injected carriers in the continuum states of surrounding bulk material, in which the carrier density is diluted and the higher-order carrier-density-dependent recombination processes are much smaller. This allows the inversion level to build up to a much higher level during the pumping stage of Q switching. The possibility of using indirect-band-gap semiconductors for carrier storage is also discussed. Using a functional device as an example, we have shown that the proposed scheme is realistic.

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