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Reduced threshold current of a quantum dot laser in a short period superlattice of indirect-band gap

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Reduced threshold current of a quantum dot laser in a short period superlattice of indirect-band gap

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We propose the idea of making quantum dot lasers by embedding direct-band gap quantum dots in a short period superlattice whose band gap is indirect. This technique reduces the threshold current and its temperature dependence. We show that a higher characteristic-temperature T_0 can be achieved in a quantum dot laser with indirect GaAs/AlAs superlattice barriers compared to that with direct GaAs barriers. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1751606]

The driving force behind the quantum dot (QD) laser studies has been the possibility of reducing the laser threshold since the density of states (DOS) in QDs is ideally much narrower than the DOS in bulk and quantum-well semiconductors. Although the progress in QD lasers has been significant, they still have not fulfilled their promise because present QD lasers still exhibit strong exponential dependence of their threshold upon temperature due to carrier recombination in the barrier layers that "clad" the QDs.[1] The characteristic temperature T_0 has been reported to have reached 161 K for *p*-type modulation doped 1.3 μm InAs/GaAs QD lasers.[2] Although this represents an improvement over that of quantum well lasers, it is much less than the predicted "infinite" values that makes the QD lasers temperature insensitive. The main reason for this lack of progress is that a substantial fraction of carriers reside not in QDs but in the surrounding material (barriers) since the QD DOS is much less than that of barriers. Furthermore, this fraction increases with the rise in temperature. As a result, the lasing threshold increases with temperature as the recombination of carriers in barriers becomes more significant. A number of ideas had been put forward to reduce the recombination in the cladding, typically using the tunneling injection schemes wherein the electrons and holes tunnel into the QDs from two opposite sides—making the cladding recombination an indirect process in real space.[3,4] This scheme relying upon a resonant process, however, is applicable only to a single layer of QDs and vulnerable to inhomogeneous broadening and charging effects.

In this letter, we propose a QD laser in which the direct-band gap QDs are embedded in a semiconductor barrier material that has an indirect band gap. We show that this technique reduces the threshold current as well as its dependence on temperature. Specifically, we have studied InAs QDs in an indirect short period $(GaAs)_6(AlAs)_6$ superlattice (SL) with a period of 35 Å.[5–8] Figure 1 shows the band structure of two InAs QD lasers formed on thin wetting layers (WL) that are confined by a larger band gap material; one with the direct GaAs barriers and the other with the indirect SL barriers. The choice of this SL with a lattice parameter almost equal to that of GaAs is made in anticipation of investigating similar InAs QDs in both direct and indirect barriers. Using a short period SL rather than a simple-indirect $Al_xGa_{1-x}As$ $(x>0.42)$ alloy provides double benefit. First of all, it is well known that both the conduction band (CB) edge[9] and the index of refraction[10,11] in the indirect $Al_xGa_{1-x}As$ decreases

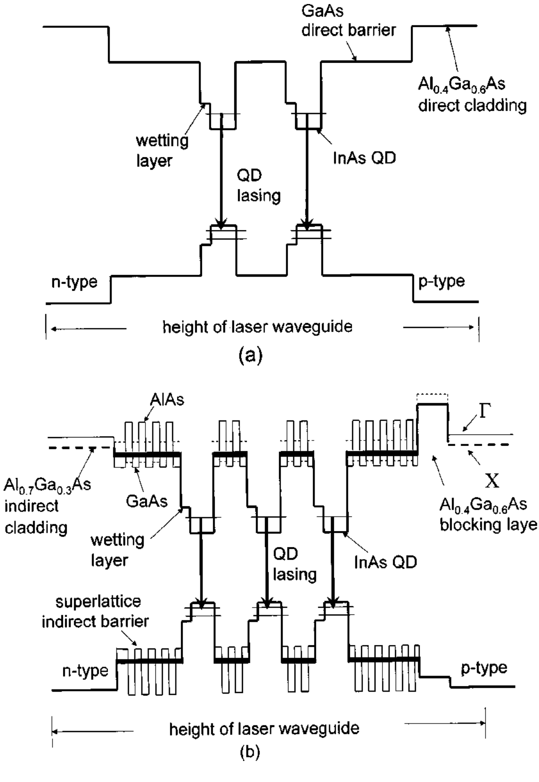

FIG. 1. Illustration of QD band structure on thin wetting layers surrounded by (a) GaAs barriers of direct band gap and (b) short period $(GaAs)_6(AlAs)_6$ SL barriers of indirect band gap in a waveguide structure.

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with the increase of Al composition. Hence, electrons are more likely to be localized in layers with higher Al composition, while photons tend to be confined in lower Al layers. This makes effective confinement of both carriers and photons necessary for laser operation unattainable. In the short period $(\mathrm{GaAs})_n(\mathrm{AlAs})_n$ SL, the CB edge is substantially (>100 meV for $n=6$) lower than that of disordered $\mathrm{Al}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As}$ alloy. Therefore, combining the $(\mathrm{GaAs})_6(\mathrm{AlAs})_6$ SL with $\mathrm{Al}_{0.7}\mathrm{Ga}_{0.3}\mathrm{As}$ alloy cladding allows for both carriers and photons to be confined in the waveguide. The second advantage is that it has indirect character in both real and inverse wave vector spaces, i.e., the electrons are confined primarily in the X-states of AlAs layers while the holes in the Γ states of GaAs layers, which leads to very long recombination times (up to a few hundred nanosecond to microsecond range.[8,12] The longer effective carrier lifetime due to the indirect nature of the band gap reduces the demand on the pumping current for maintaining those carriers in the barrier, thus a higher T_0 can be obtained.

The proposed waveguide of $(\mathrm{GaAs})_6(/\mathrm{AlAs})_6$ SL with $\mathrm{Al}_{0.7}\mathrm{Ga}_{0.3}\mathrm{As}$ cladding has a relatively small CB offset (~ 75 meV). This offset may not be sufficient to prevent electrons from reaching the p-type contact where the parasitic recombination can take place. To avoid this problem a thin (200 Å) blocking layer of $\mathrm{Al}_{0.4}\mathrm{Ga}_{0.6}\mathrm{As}$ is inserted between the $(\mathrm{GaAs})_6(/\mathrm{AlAs})_6$ SL and the p-type $\mathrm{Al}_{0.7}\mathrm{Ga}_{0.3}\mathrm{As}$ cladding as shown in Fig. 1(b). The blocking layer with ~ 150 meV CB offset plays the same role as in Ref. 4, but, unlike Ref. 4, the blocking layer can be placed at a significant distance form the QDs.

The carrier distribution within the barrier-WL–QD system with N_b, N_w, and N_d is calculated based on quasiequilibrium within the CB and valence band (VB). The injected current density is related to the carrier distribution within the different regions of the QD structure as

$$J=e\left(\frac{N_b}{\tau_b}+\frac{N_w}{\tau_w}+\frac{N_d}{\tau_d}\right), \tag{1}$$

where the minority carrier lifetime $\tau_w=2$ ns for WL, and $\tau_d=1$ ns for QDs, $\tau_b=2$ ns for direct GaAs barriers and $\tau_b=100$ ns for indirect SL barriers. Specifically, for InAs QDs formed on thin InAs WLs with base width of $b=10.2$ nm in GaAs barriers, there is one confined electron state at 160 meV below the GaAs CB, and two hole states at 137 meV and 115 meV above the GaAs VB.[13] The ground states in WL are 40 meV below the GaAs CB and 88 meV above the GaAs VB.[14] The result of electron distribution is shown in Fig. 2 for a total injected carrier density of $8\times 10^{10}/\mathrm{cm}^2$ needed to saturate the ground states of InAs QDs with an area density of $4\times 10^{10}/\mathrm{cm}^2$ at $T=0$. Figure 2 shows that even for this low injected carrier density, at room temperature, the percentage of electrons residing in the barrier region well surpasses that in the QDs. The reduction of carrier recombination in barriers resulting from the increase of minority carrier lifetime should in principle reduce the threshold pumping current.

In order to make a fair comparison,[15] we have chosen InAs QDs with smaller base widths to be embedded in the short period $(\mathrm{GaAs})_6(\mathrm{AlAs})_6$ SL barriers with a band gap wider than that of GaAs so that the QD confined states with approximately the same localized energies as in InAs/GaAs QDs can be used in the calculation. The two waveguide structures under investigation have the following parameters: for the direct GaAs, the lasing wavelength $\lambda=1.03$ μm, the indexes of refraction are $n(\mathrm{GaAs})=3.5$ in barriers and $n(\mathrm{Al}_{0.4}\mathrm{Ga}_{0.6}\mathrm{As})=3.27$ in cladding layers; for the indirect SL, $\lambda=0.82$ μm, $n(\mathrm{SL})=3.28$, and $n(\mathrm{Al}_{0.7}\mathrm{Ga}_{0.3}\mathrm{As})=3.15$. The contrast in index of refraction for the structure with indirect SL is almost half of that with direct GaAs, but this is at least partially compensated by the shorter wavelength in the QD laser with indirect SL barriers. We have calculated the maximum attainable confinement factors for both structures. They are obtained at different waveguide thicknesses: $d_w(\mathrm{GaAs})=0.22$ μm for GaAs barriers and $d_w(\mathrm{SL})=0.3$ μm for SL barriers. The ratio of vertical confinement factors in the growth direction between the two structures was found to be $\Gamma_{\mathrm{dir}}/\Gamma_{\mathrm{ind}}=1.5$. In order to have the same modal gain in the two QD lasers, we have to allow more QDs in the structure with indirect SL as compared to that with direct GaAs at a ratio of 3/2. We have chosen to employ two layers of QDs in GaAs [Fig. 1(a)] and three layers in SL [Fig. 1(b)], with an area density of $4\times 10^{10}/\mathrm{cm}^2$ and $6\times 10^{10}/\mathrm{cm}^2$, respectively. As a result, both structures can have the same total optical confinement factor ($\Gamma=1.4\times 10^{-4}$).

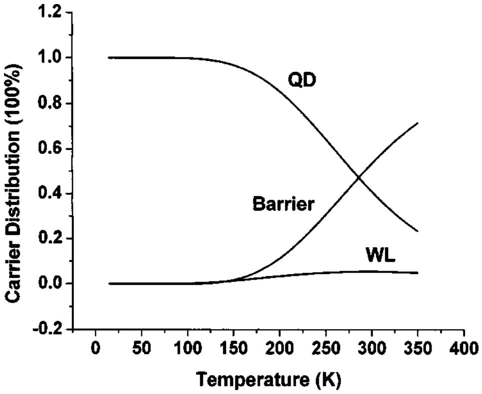

FIG. 2. Percentage of electron population distribution between barrier, WL, and QDs for InAs QDs in GaAs barriers of direct band gap as a function temperature for a total injected carrier density of 8×10^{10} cm^2.

For a typical QD ensemble, it is reasonable to assume that the inhomogeneous broadening of the transition linewidth induced by the dot-size variation is much larger than the homogeneous broadening. The Lorentzian function can therefore be approximated by a δ function, and the optical gain between the lowest electron and hole states is given as

$$g(\hbar\omega)=\frac{2\pi e^2 M_b^2\Gamma}{m_0^2\varepsilon_0 c n_r \omega V_0}P(\hbar\omega,\sigma_E)[f_c(\hbar\omega)-f_v(\hbar\omega)], \tag{2}$$

where m_0 is the free electron mass, ε_0 is the permittivity in vacuum, c is the speed of light in vacuum, n_r is the index of refraction at the transition, $\hbar\omega$ is the average transition photon energy, M_b is the momentum matrix element for bulk InAs with $M_b^2/m_0=3.0$ eV,[16] V_0 is the average volume of the QD ensemble, and $f_c(\hbar\omega)$ and $f_v(\hbar\omega)$ are the electron occupation probability at the QD electron and hole ground states, respectively. The energetic broadening function is given by

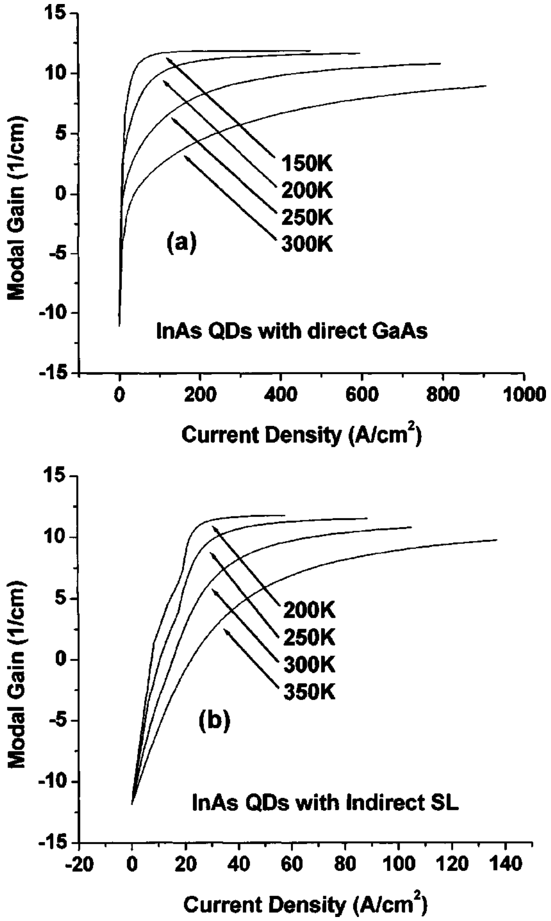

FIG. 3. Modal gain as a function of pumping current density at various temperatures for InAs QDs in barriers of (a) direct GaAs and (b) indirect SL.

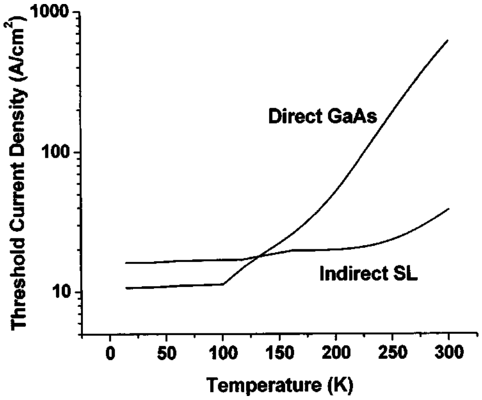

FIG. 4. Pumping threshold current density as a function of temperature to maintain threshold gain of 8/cm for InAs QDs in direct GaAs and indirect SL barriers.

$$P(E,\sigma_E)=\frac{1}{\sigma_E\sqrt{2\pi}}\exp\left[-\frac{(E-\hbar\omega)^2}{2\sigma_E^2}\right] \qquad (3)$$

with an inhomogeneous broadening width of $\sigma_E = 20$ meV.

The results of optical gain at the average transition photon energy are shown in Fig. 3. Figure 3 shows that the optical gain increases with the pumping current density and reaches saturation value at approximately 12/cm. Comparing between Fig. 3(a) and Fig. 3(b), we can see that QD lasers with indirect SL barriers require less pumping current than those with direct barriers to reach the same level of optical gain, especially at higher temperatures. The temperature dependence of the threshold pumping current is better illustrated with the assumption of a fixed value of optical gain that is required to compensate the typical losses (2/cm to 10/cm) found within QD laser cavities. Taking the value of threshold gain at $g_{\text{th}} = 8$/cm, we have calculated the threshold current density J_{th} as a function of temperature for both structures (Fig. 4). Figure 4 reveals that the QD laser with indirect SL barriers has a slightly larger threshold current at lower temperatures ($T < 130$ K). This is because a higher pumping current is required to populate the higher number of QDs in indirect SL structure. We also notice that in the low temperature region $T < 100$ K, the threshold current stayed almost constant for both structures since the carrier population in the barrier regions is very small, and practically all carriers injected by the pumping current went to the QD states. A rather significant difference in J_{th} between the two cases at higher temperatures is the direct result of the lifetime difference between the two types of barriers where there is an inevitable carrier buildup. We have fitted our data to the standard threshold-temperature expression: $J_{\text{th}} = J_0 \exp(T/T_0)$. We have obtained $T_0 = 50$ K for the QD laser structure with direct GaAs barriers in the temperature range of $T > 100$ K and $T_0 = 216$ K for the indirect SL barriers in $T > 150$ K—a significant improvement on the temperature characteristics of threshold.

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