Optical gain and loss in 3 μm diode "W" quantum-well lasers

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Gain in broad-area midinfrared diode "W" lasers ($\lambda = 3-3.1$ μm) has been measured using lateral mode spatial filtering combined with the Hakki–Paoli approach. The internal optical loss of $\approx$19 cm^{-1} determined from the gain spectra was the same for devices with either ten or five period active regions and nearly constant in the temperature range between 80 and 160 K. Analysis of the differential gain and spontaneous emission spectra shows that the main contribution to the temperature dependence of the threshold current is Auger recombination, which dominates within almost the entire temperature range studied (80–160 K).
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Considerable progress has been made in the development of midinfrared interband type-II optically pumped and diode lasers.[1–3] Despite the spatial separation of electrons and holes at the type II heterointerface, the W-quantum well (W–QW) design of the active region[4] provides a sufficiently large optical matrix element. At the same time it permits a large variation of the lasing wavelength controlled by the active region layer thickness and barrier height.

Performance of diode W–QW lasers degrades rapidly with increasing temperature. The highest reported heat sink temperature for cw operation of diode W–QW lasers is 200 K,[1] while for the optically pumped devices it is 290 K.[2] In this letter we study the temperature dependences of the optical gain and spontaneous emission spectra as well as the optical loss and differential gain of diode W–QW lasers. We find that, in contrast with optically pumped devices,[5–7] in both five and ten period devices the internal loss is almost the same and remains nearly constant in the temperature range from 80 to 160 K. The temperature increase of the threshold current can be explained by the dominant role of Auger recombination at high carrier concentrations combined with the linear temperature increase of the threshold concentration.

The diode W–QW laser structures were grown by molecular beam epitaxy. An *n*-type GaSb substrate was followed by a lattice-matched 1.5-μm-thick *n*-type AlGaAsSb optical cladding layer ($N_D = 2\times10^{17}$ cm^{-3}), a lattice matched 0.6-μm-thick AlGaAsSb separate confinement heterostructure (SCH) layer, a hole blocking region (in some structures), consisting of seven periods 14 Å AlSb/15 ÅInAs, W–QW active region, consisting of five or ten periods of 80 Å $Al_{0.15}GaAs_{0.05}Sb_{0.95}$/15 Å InAs/27 Å $GaIn_{0.25}Sb$/15 Å InAs, another 0.6 μm AlGaAsSb SCH layer, a lattice-matched 1.5 μm *p*-type AlGaAsSb optical cladding layer ($N_A = 5\times10^{18}$ cm^{-3}) and a 50 Å p^+-GaSb cap layer. Only 5-W–QW structures had the hole blocking region.

Gain-guided lasers with 100 μm wide stripe contacts were mounted *p* side down on a copper heat sink attached to the cold finger of a liquid nitrogen cryostat. Gain spectra were measured using the Hakki–Paoli technique adapted to broad area devices.[8] Modal gain spectra for the 10-W–QW device operated in cw mode at 80 and 160 K are shown in Fig. 1. The modal gain equals $g = N\Gamma G - \alpha_{tot}$, where N is the number of W–QWs, Γ is the optical confinement factor per well, and G is the material gain. The total loss α_{tot} has been estimated from the low energy side of the modal gain spectra, where the material gain G is sufficiently small to take $g \approx -\alpha_{tot}$. This gives $\alpha_{tot} \approx 34$ cm^{-1}. One facet of each device was coated for high reflection and the other for antireflection providing the reflectivities of $R_h = 0.95$ and $R_a = 0.05$, respectively. This corresponds to a mirror loss of $\alpha_m \approx 15$ cm^{-1}. Subtraction of α_m from the measured α_{tot} gives an internal loss of $\alpha_{int} \approx 19$ cm^{-1}. The temperature increase from 80 to 160 K leads to an apparent broadening of the gain spectrum and a redshift of the gain maximum from 0.412 to 0.397 eV, with the linear temperature tuning coefficient $\beta \approx -2\times10^{-4}$ eV/K. The full width at half maximum of the gain peak increases from 12 meV at 80 K to 20 meV at 160 K. Measurements of the total loss at 160 K give the same value within the experimental accuracy (Fig. 1). The internal loss obtained for 5-W–QW lasers is also the same within experimental accuracy.

There are three major reasons for the temperature increase of the threshold current. These are: a temperature increase of α_{tot}, a temperature decrease of the differential gain dg_n^{max}/dJ and a temperature increase of the leakage current into the cladding region. It was shown previously, that at temperatures as high as 80 °C, the hole heterobarrier leakage current in GaSb-based lasers with similar waveguide and

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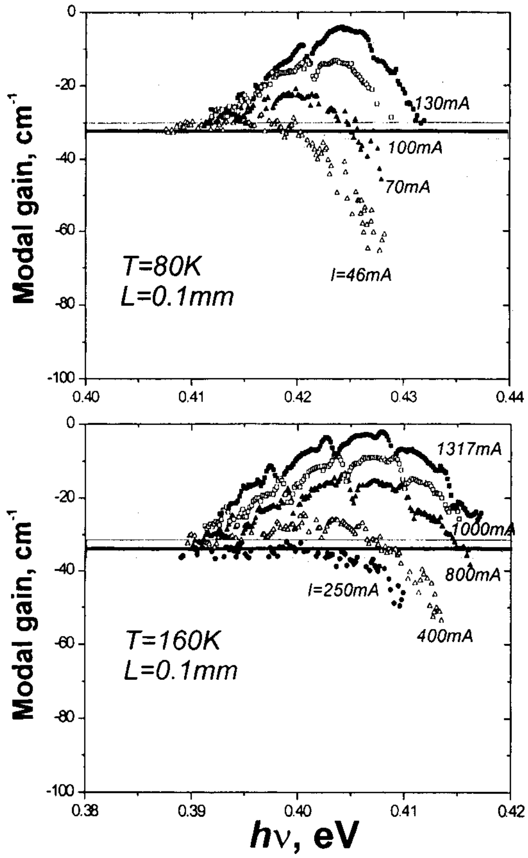

FIG. 1. Spectral dependences of the modal gain for the laser with 10-W–QWs at 80 K (upper panel) and 160 K (lower panel).

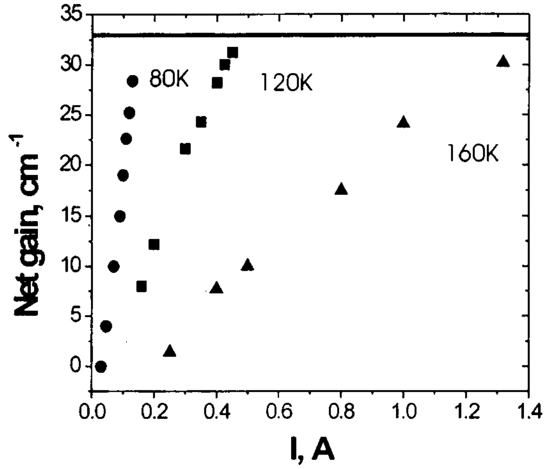

FIG. 2. Dependences of the net gain maxima on current for the sample with 10-W–QWs at three temperatures. Horizontal lines indicate $\alpha_{\rm tot}$.

cladding materials is small and cannot be a limiting factor for the high-temperature performance.[8]

We can specify two contributions to the total loss $\alpha_{\rm tot}$. First is the free-carrier absorption in the quantum wells. This mechanism is found to be dominant in multiperiod (50–80 periods) optically pumped devices, where it is responsible for more than a twofold increase of $\alpha_{\rm int}$ in the temperature range from 80 to 160 K.[5–7] The second contribution is due to modal overlap with the cladding material and light scattering in the waveguide. The fact that the internal loss does not depend strongly on either the number of wells (five or ten), or temperature strongly indicates to the conclusion that the second mechanism is dominant in these electrically pumped W–QW lasers.

Since $\alpha_{\rm tot}$ is independent of the temperature, a possible reason for the temperature increase of the threshold current is the temperature dependence of $dg_n^{\rm max}/dJ$. One can see (Fig. 2) that as the temperature increases from 80 to 160 K, the average $dg_n^{\rm max}/dJ$ decreases from $\approx$0.29 to $\approx$0.03 cm^{-1}/mA. The behavior of $dg_n^{\rm max}/dJ$ for 5-W–QW samples is qualitatively the same, except that the magnitude of $dg_n^{\rm max}/dJ$ is larger, *viz.* $\approx$0.4 cm^{-1}/mA (80 K) and $\approx$0.1 cm^{-1}/mA (120 K) for the lasers without the hole blocker; and $\approx$0.7 cm^{-1}/mA (80 K) and $\approx$0.07 cm^{-1}/mA (160 K) for the lasers with the hole blocker. This may indicate an inhomogeneous carrier distribution among the wells in the 10 W–QW devices, which reduces the effective number of wells[9] and suppresses $dg_n^{\rm max}/dJ$.

The net gain maximum $g_n^{\rm max}$ can be expressed in terms of two-dimensional (2D) carrier concentrations as[10,11]

$$g_n^{\rm max}=N\Gamma G_0\left\{1-\exp\left[-\frac{\pi\hbar^2}{m_c^*}\frac{n(J,T)}{T}\right]-\exp\left[-\frac{\pi\hbar^2}{m_v^*}\frac{p(J,T)}{T}\right]\right\}, \quad (1)$$

where G_0 is a weak function[11] of T, n, $p(I,T)$ are the electron and hole concentrations in the wells, and m_c^*, m_v^* are the electron and heavy hole effective masses. The electron and hole concentrations are assumed to be equal and, for simplicity, broadening of the energy levels is not taken into account. To obtain information about the current and temperature dependences of the carrier concentration $n(J,T)$ we analyzed the spontaneous emission (SE) spectra collected from a side of the device.[12] A 0.5 mm slit was used to filter out the stimulated emission contribution from the laser facets. Dependences of the integrated spontaneous emission intensity $I_{\rm sp}$ on current below the threshold are shown in Fig. 3. The dependence $I_{\rm sp}(J)$ is linear at 80 K, while at higher temperatures a region $I_{\rm sp}\sim J^{2/3}$ appears as the threshold increases. This dependence can be interpreted as a result of

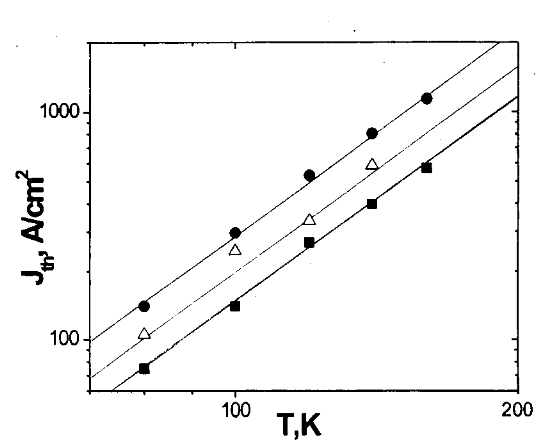

FIG. 3. Current dependences of the integrated luminescence intensity $I_{\rm sp}$ at 80 K (open circles) and 160 K (solid circles). The arrows mark the lasing thresholds. The fitting lines are: $I_{\rm sp}\sim J$ for 80 K and $I_{\rm sp}\sim J^{2/3}$ for 160 K. The inset is the dependence of $I_{\rm sp}$ on inverse temperature for $I=0.1$ A (1) and 0.3 A (2).

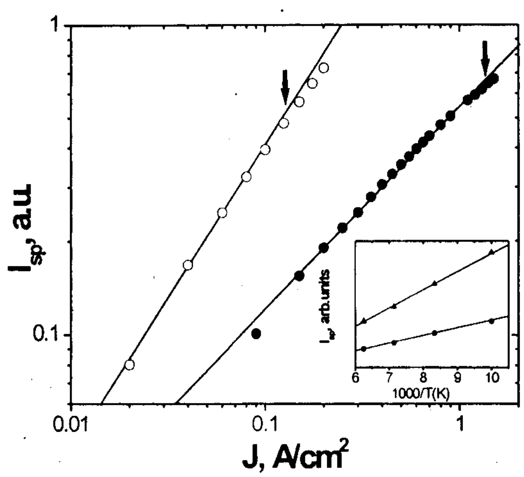

FIG. 4. Temperature dependences of J_{th} for the samples with 10 W–QWs (solid circles), 5 W–QWs without the hole blocker (triangles) and 5 W–QWs with the hole blocker (open circles), on a double logarithmic scale. The fitting lines are $J_{th} \sim T^3$.

bimolecular radiative recombination when the carrier concentration is controlled by the Auger process.[12] The radiative recombination rate coefficient in the 2D case is proportional to $1/T$. One can see that within experimental accuracy I_{sp} is a linear function of $1/T$ (inset in Fig. 3), even at the current of 300 mA, where Auger recombination already dominates. This means that within the temperature range from 80 to 160 K the carrier concentration in the active area does not depend strongly on temperature at a fixed current. This in turn implies that the Auger coefficient does not significantly depend on temperature, for if it did the concentration could surely vary. A slow variation with T is consistent with previous findings.[13] For fixed α_{tot} the threshold carrier concentration n_{th} must be proportional to T in order to fulfill the threshold condition $g_n^{max} = \alpha_{tot}$. A linear temperature increase of n_{th} determines the temperature dependence of the threshold current, associated with Auger recombination as $I_A \sim T^3$. Figure 4 shows dependences of the threshold current on temperature in the samples with 5- and 10-W–QWs. The approximation $J_{th} \sim T^3$ is in excellent agreement with experiment, i.e., I_A gives the main contribution to the J_{th}.

To obtain information about the effect of laser heating on the experimental results, we estimated an additional temperature increase ΔT of the active area in cw mode from the energy shift between the SE spectra recorded in pulsed (100 ns, 2% duty cycle) and cw modes at (160 K). Although ΔT is relatively small (<5 K) at cw currents below 800 mA, it reaches 15–20 K at the current ≈ 1.3 A. This corresponds to a specific thermal resistance of ≈ 11 K cm^2/kW.

In conclusion, we have experimentally investigated the optical gain and internal loss in 3 μm type II W diode lasers. The internal optical loss is ≈ 19 cm^{-1} for devices with both a 5- and 10-W–QW active regions and remains nearly constant within the temperature range 80–160 K. This implies that the main contribution to the internal optical loss is the waveguide and cladding loss rather than free carrier absorption in the wells. Analysis of the spontaneous emission spectra shows that the reason for the temperature increase of the threshold current is Auger recombination.

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