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Mechanism of the temperature sensitivity of mid-infrared GaSb-based semiconductor lasers

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The sources of temperature sensitivity of the threshold current in type-I and type-II mid-infrared semiconductor lasers are investigated. Measurements of the interband optical absorption allow direct comparison of the optical matrix elements in laser structures with type-I and type-II band alignments and prove that the difference in the optical matrix elements is insignificant for these two groups of structures. We show that thermally-induced hole escape from the active quantum wells strongly deteriorates the optical emission in both type heterostructures. Experiments show that the temperature decay of PL is generally stronger for type-II samples. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2001132]

Type II semiconductor heterostructures are promising for mid-IR laser applications. Type II band alignment provides an opportunity to control wavelength in a wide spectral range by changing the quantum well widths rather than material composition. However, the temperature performance of type II mid-IR quantum well lasers is still a crucial issue for successful fabrication of electrically pumped continuous wave (cw) operated device in the practically important 3–4 μm spectral range. The highest reported cw operation temperatures were 214 K ($\lambda=3.4$ μm)[1] and 217 K ($\lambda=3.2$ μm).[2] Being characterized by relatively low threshold current densities at cryogenic temperatures ($J_{\text{th}}\sim 10$ A/cm^2, $T=78$ K in type II intersubband cascade layers[1]), type II mid-IR lasers show strong performance degradation as the temperature increases up to 300 K. The typical values of parameter T_0 characterizing exponential increase of the threshold current with temperature were reported for the diode type II mid-IR lasers in the range of 30–50 K,[3] which is inferior to both type I quantum well lasers with shorter wavelength ($T_0=83$ K, $\lambda=2.5$ μm)[4] and intersubband quantum cascade lasers with longer wavelength ($T_0=195$ K, $\lambda=4.8$ μm).[5]

The following factors can result in low T_0 of type-II mid-IR devices: (i) temperature increase of the optical loss, (ii) low differential gain due to reduced electron and hole wave function overlap, (iii) thermally activated carrier escape from the active quantum wells due to insufficient hole confinement, and (iiii) possible enhancement of the nonradiative recombination rate in nonoptimized structures. Previous studies[6] exclude the temperature dependence of the optical loss as a reason for low T_0 in mid-IR lasers. In this work, to analyze factors (ii) and (iii) we compare the optical properties of type-I and type-II Sb-based heterostructures measuring the optical absorption and photoluminescence temperature quenching in the spectral range near the heterostructure optical edge.

We study two groups of samples (group I and group II) with predominantly type I and type II band alignment. Each group consists of two structures which are characterized by different hole confinement; see Table I. The hole confinement energies were calculated using the material parameters given in (Ref. 7). Calculated band profiles and positions of energy levels participating in optical transition are presented in Fig. 1. The structures have been grown by MBE on GaSb substrates. In group I structures, two compressively strained InGaAsSb quantum wells are incorporated in the $Al_{0.25}Ga_{0.75}As_{0.022}Sb_{0.978}$ waveguide core sandwiched between $Al_{0.9}Ga_{0.1}As_{0.075}Sb_{0.925}$ cladding layers lattice matched to GaSb substrate. Group II structures consist of GaSb-matched $In_{0.2}Ga_{0.8}As_{0.18}Sb_{0.82}$ waveguide with six quantum wells. These wells represent InAs/$Ga_{0.6}In_{0.4}$Sb/InAs layers (W-type quantum wells, sample 1–II)[8] or a single InAs quantum well layer (sample 2-II).[9] The cladding material in both cases is $Al_{0.9}Ga_{0.1}As_{0.09}Sb_{0.91}$. The excitation source is Q-switched Nd:YVO$_3$ laser, $\lambda=1.064$ μm, with the repeti-

TABLE I. Structure parameters.

	QW material	QW width nm	Waveguide material	Cladding material	λ (13 K) μm	Hole confinement meV
1-I	$In_{0.41}GaAs_{0.14}Sb$	10	$Al_{0.25}GaAs_{0.022}Sb$	$Al_{0.9}GaAs_{0.075}Sb$	1.96	60
2-I	$In_{0.50}GaAs_{0.25}Sb$	14.5	$Al_{0.25}GaAs_{0.022}Sb$	$Al_{0.9}GaAs_{0.075}Sb$	2.49	0
1-II	InAs/$In_{0.4}$GaSb/InAs	1.65/2.4/1.65	$In_{0.2}GaAs_{0.18}Sb$	$Al_{0.9}GaAs_{0.09}Sb$	3.69	80
2-II	InAs	2.4	$In_{0.2}GaAs_{0.18}Sb$	$Al_{0.9}GaAs_{0.09}Sb$	3.45	0

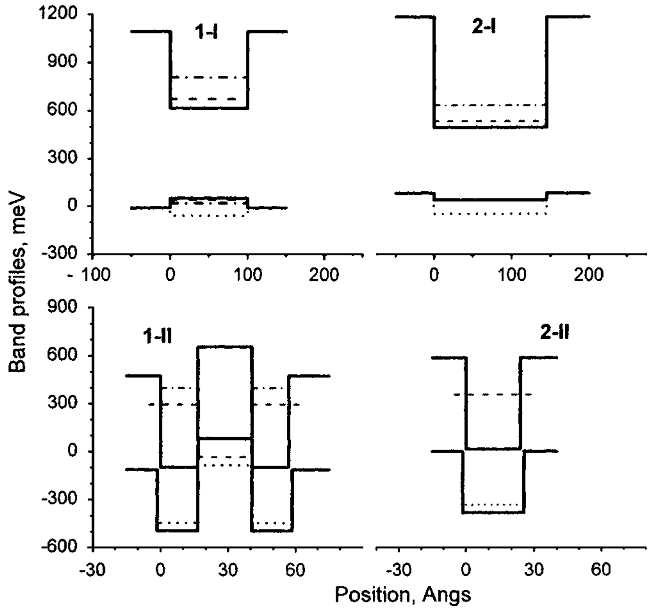

FIG. 1. Band profiles and energy levels of the structures. Solid line shows band positions for conduction and heavy-hole bands, dotted line shows the light-hole band split by the strain. Level positions: dashed line—first (lowest) levels of electrons and holes, dashed-dotted lines—second levels.

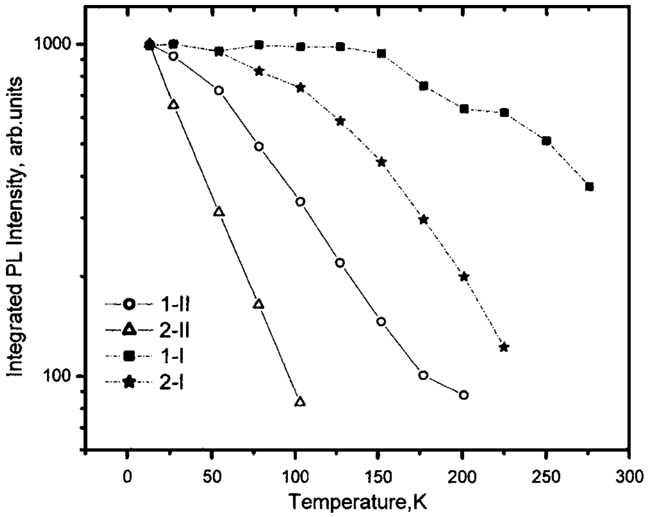

FIG. 3. Integrated PL intensity as a function of temperature. Pumping power density is ~200 W/cm^2 per well.

tion frequency 200 kHz, pulse duration ~80 ns, and the average power 80–170 mW.

Absorption spectra were obtained from the PL spectra collected from the edge of the sample while a fixed-sized pumped region was moved to a varying distance from the edge.[10] This technique allows measuring the absorption spectrum of a structure containing small number of quantum wells. Figure 2 shows the absorption spectra for type I (1-I) and W type II (1-II) samples. The results of the measurements were renormalized with respect to the number of quantum wells and optical confinement in the absorbing structures. The maximum absorption per quantum well in the type I structure was only about 50% higher than in type II structure. This makes the optical matrix element in type II structures only 1.2 times lower than in type I structures, which correlates well with calculations.[11] We, therefore, rule out the reduced optical gain as a mechanism for the inferior temperature performance of type II mid-IR lasers.

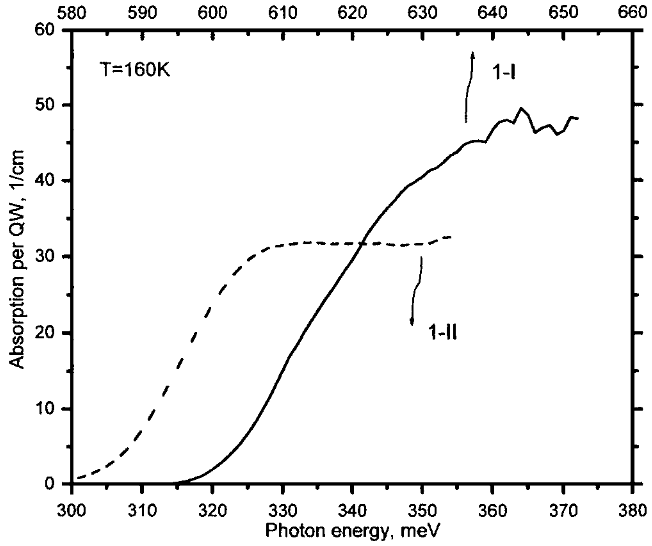

FIG. 2. Optical absorption per quantum well for samples 1-I (dashed line) and 1-II (solid line).

To study the recombination in type I and type II structures, we measured the integrated PL intensity as a function of temperature; see Fig. 3. For convenience, all the curves are normalized to the lowest-temperature value. The high-temperature decay of the PL is due to thermal depopulation of the quantum wells. Our data are consistent with the model,[12,13] experiments[14] and recent results of Ongstad *et al.* (to be published in JAP), which demonstrate the important role of the hole escape for temperature performance of type II lasers. The strength of the PL temperature quenching in each group of structures correlates well with the degree of the hole confinement. The smaller the hole confinement energy, the stronger is the temperature decrease of the PL intensity.

The character of temperature dependence of the PL correlates with T_0 values for studied laser structures. Structure 2-II, intentionally designed with no hole confinement, shows stronger PL temperature decay and lower $T_0=39$ K[7] than structure 1-II ($T_0=49.3$ K),[8] where the hole confinement energy was calculated as 80 meV. From Fig. 3 one can see that temperature decay of PL is generally stronger for type II samples. Besides, there is a major difference in the shape of the curves between type I and type II samples. While in 1-I structure with strong hole confinement the PL decay starts at about 170 K, the structure I-II, where the hole confinement is even higher, shows a decrease in the PL intensity, starting from the lowest experimental temperature of 13 K. The same relation holds for structures 2-I and 2-II with no hole confinement. In the structure 2-I the integrated PL intensity is almost temperature independent up to 50 K, while in 2-II the PL intensity drops three times in the same temperature range. Low temperature sensitivity of integrated PL intensity in type I structures can be explained assuming that the radiative recombination is the main process determining the steady state carrier concentration in the quantum wells. Under this condition, the temperature decrease of radiative recombination rate is compensated by corresponding increase of steady state carrier concentration and the resulting temperature dependence of the integrated PL is weak. At higher temperatures, thermally activated carrier escape leads to PL quenching.

The nature of the observed difference in temperature dependencies of photoluminescence for type I and type II structures is not fully understood. One of the possibilities is an excessive nonradietive losses which can be associated with interface assisted recombination in narrow QWs.[15,16]

In conclusion, we carried out direct measurements of the optical band-edge absorption in laser structures with type II and type I band alignments and found no considerable difference in the optical matrix elements. This small difference cannot explain strong temperature sensitivity of the threshold current observed in type II mid-IR lasers. Thermally induced carrier escape from the active quantum wells strongly deteriorates the optical emission in both type-I and type-II heterostructures. Different temperature behavior of PL in type I and type II structures observed in our experiment cannot be explained in the framework of a simple model of the hole thermal escape from the wells.

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