Extended Abstracts of the 15th Conference on Solid State Devices and Materials, Tokyo, 1983, pp. 341-344

4-5 μm Emissions from InGaAsP/InP Lasers —Evidence for Excitations in Split-Off Valence Band—

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4-5 μm wavelength emissions associated with recombinations of holes in the split-off valence band and electrons in the light-hole valence band were observed from 1.3 μm and 1.5 μm InGaAsP/InP lasers. Hole populations in the split-off valence band are dramatically increased with the current level and with the temperature rise. It was deduced from their current dependence as well as that of acoustic signals reported so far that Auger recombination is a most probable mechanism up to about a half of the threshold current and intervalence band absorption and its saturation behavior mainly influences the lasing characteristics above that current.

§1. Introduction

InGaAsP/InP double-heterostructure (DH) lasers are expected to be light sources in optical-fiber communications, but the sensitive temperature dependences of the threshold currents have been a big problem. Among several models proposed so far,[1-3] Auger recombinations and intervalence band absorption seem to be the most important mechanisms.[4,5] Recently, Mozer et al. observed emission with an energy close to $E_g+\Delta$ which is associated with recombination of holes in the split-off valence band and electrons in the conduction band from 1.3 μm InGaAsP DH lasers, demonstrating the participation of the split-off valence band in these mechanisms.[5]

In this paper, we show another evidence for hole excitations in the split-off valence band by observing long wavelength (4.3-5.0 μm) emissions associated with recombinations of holes in the split-off valence band and electrons in the light-hole valence band from both 1.3 μm and 1.5 μm InGaAsP DH lasers. The relations between the hole populations in the split-off valence band and the loss mechanisms will be clarified from the current dependence of emissions as well as that of acoustic signals reported so far.[6-8]

§2. Experiment

Measurements were performed on buried-heterostructure (BH) InGaAsP/InP lasers of 1.3 μm and 1.5 μm wavelengths. The active layer width and thickness were about 2 μm and 0.2 μm, respectively. The devices were bonded p-side down to copper heat sinks with In-bonding layers and were driven by current pulses of 50% duration at a 1 kHz frequency. Lasing light output was detected by a Ge photo diode from the axial direction of the laser, while 4-5 μm wavelength emissions were detected by a PbSe photo-conductive cell from the side of the

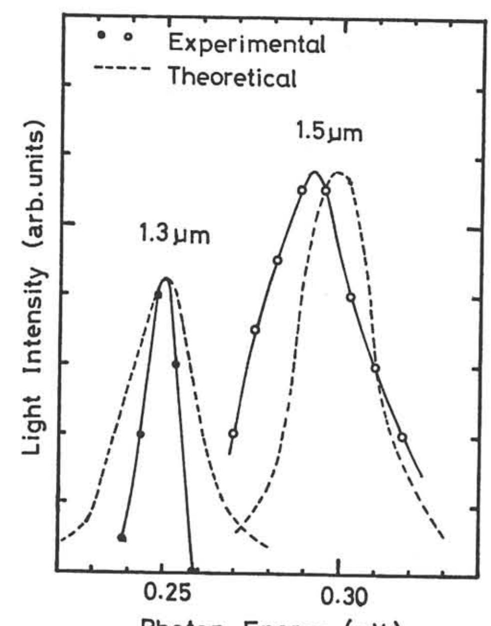

Fig. 1 Long wavelength emission spectra observed from 1.3 μm and 1.5 μm BH InGaAsP lasers. Theoretical curve is normalized to the experimental maximum.

active stripe through the covering InP layer through a low pass filter of which cut-off wavelength is 2.4 μm. The detected signals were amplified by a lock-in amplifier. In our experiment, $E_g + \Delta$ emission was too weak to be detected and the crossover with the band to band recombination in the InP layers[5] made the results unreliable.

Typical 4-5 μm wavelength emission spectra observed from 1.3 μm and 1.5 μm InGaAsP BH lasers are shown in Fig. 1. The emission peaks and profiles were almost invariant with the current level and with the temperature. These emissions were identified as recombination of holes in the split-off valence band and electrons in the light-hole valence band by theoretical calculations(dashed line in Fig. 1). On the calculation, we postulated a Boltzmann distribution for holes in the split-off valence band and k-selection rule for transitions and determined the band structure with k.p perturbation theory.[8] The spectrum peaks correspond to the critical point of the joint-density of states due to the large effective density of states. A possibility of emissions from radiative recombination centers in the band gap will be excluded from the following two points. The one point is the photon energy difference between the 1.3 μm and 1.5 μm compositions. If the emissions are originated from the same kind of recombination centers, the photon energy of the 1.5 μm composition will be smaller than or at least equal to that of the 1.3 μm one. The other point is their unique current dependences and the high temperature dependence which will be shown in the following section. Also, large increase above threshold currents will not be expected for emissions from recombination centers which will be proportional to carrier densities in the band.

The dependence of the integrated 4-5 μm wavelength light intensity on current level at different temperatures is shown in Fig. 2. The current is normalized with the threshold current for comparison of lasers with different threshold currents. At very low current below I_{th}, the light intensity increases with the slope of 1.6-1.9 in the logarithmic plot. At about 0.5 I_{th}, the intensity stays constant and increases again. These characteristics indicate that populations in the split-off valence band are drastically increased with current level but with a peculiar dependence.

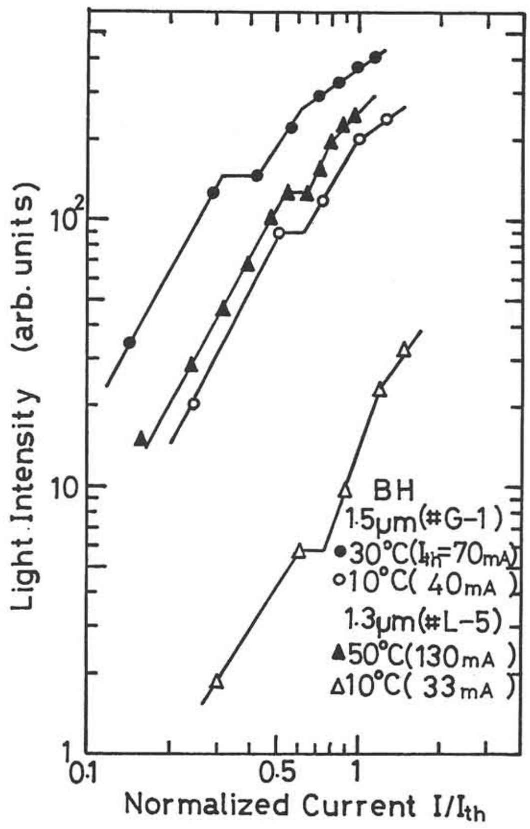

Fig. 2 Double logarithmic plot of the integrated 4-5 μm emission light intensity vs. normalized current for 1.3 μm and 1.5 μm BH lasers at different temperature.

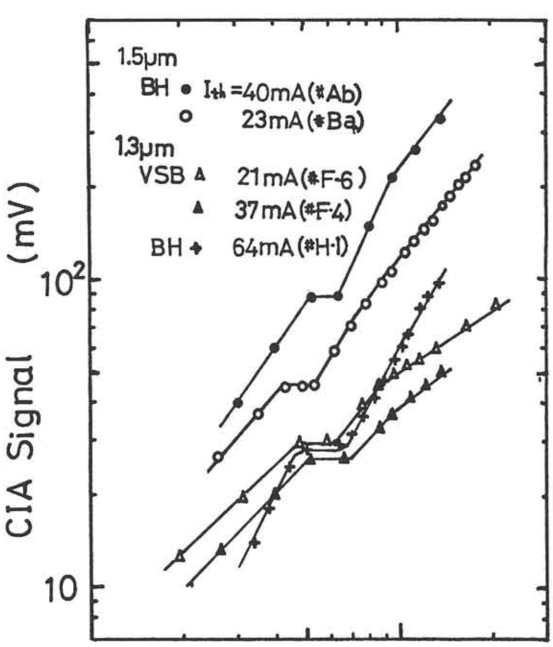

Fig. 3 Double logarithmic plot of CIA signal vs. normalized current for 1.3 μm and 1.5 μm lasers with different structures and different threshold currents at room temperature.

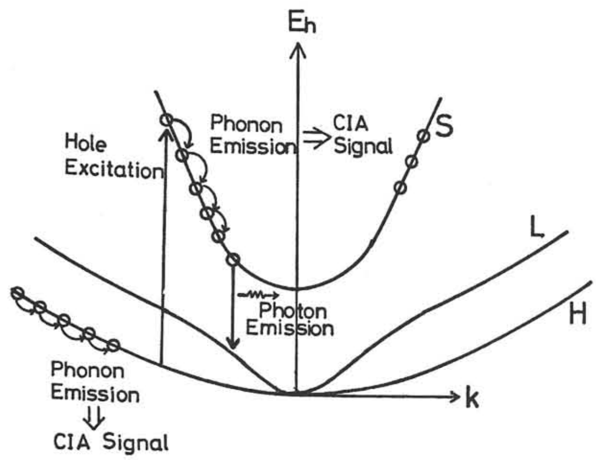

Fig. 4 Schematic diagram of hole excitations to the split-off valence band and hole relaxation processes associated with LO phonon emission and long wavelength photon emission.

For better understanding, let us compare the results with that of current-injection-induced acoustic (CIA) signals reported so far.[6,8] Figure 3 shows the typical current dependence of the CIA signals for 1.3 μm and 1.5 μm BH and 1.3 μm V-grooved substrate buried heterostructure (VSB) InGaAsP/InP lasers with different threshold currents. Remarkable similarity of the two independent results in Figs. 2 and 3 will be evident. The relation between the two results may be depicted as follows. When holes are excited by the Auger recombination and/or the intervalence band absorption as shown in Fig. 4, they relax to the band minima by successively emitting longitudinal optical (LO) phonons or interacting directly with the electron gas.[9] The CIA signals are mainly caused by acoustic phonons emitted by the LO phonons. Therefore, both the 4-5 μm wavelength emission and the CIA signal will be proportional to hole excitations into the split-off valence band. CHSH Auger process is probably a main mechanism of this hole excitations at low current density, i.e., at low light intensity. The incremental slope of 1.6-1.9 in Fig. 2 in the low current region is not unreasonable compared with the reported data.[10] The slope of the CIA signal in Fig. 3 in the corresponding current region seems to be scattered. The reason is not fully understood at present.

The saturation of the CIA signal at around 0.5 I_{th} was estimated to be due to superradiance by the consideration of the relation between the saturation of the CIA signal and the lasing threshold currents for GaAlAs DH lasers.[6,11] It was the conclusion that most of the input energy begins to be consumed effectively as a radiative energy within the InGaAsP lasers well below the threshold currents. The increase of the CIA signal above the saturation level was explained theoretically on the intervalence band absorption model.[7,8] The CIA signal increment above the saturation level vs. lasing light output is shown in Fig. 5 for 1.3 μm VSB and 1.5 μm BH lasers as well as for a 1.3 μm BH laser already reported.[6] The linear portion indicates that the intervalence band absorption coefficient is constant and hole excitation to the split-off valence band is proportional to lasing light intensity. The decrease of the incremental slope to a value of 0.2 above the threshold currents indicates that the absorption coefficient is decreasing and the transition rate saturates for intense lasing light. This is due to hole-burning of the hole population in the heavy-hole band.[12] The CIA signal increment of the 1.5 μm BH laser is about three times larger than that of the 1.3 μm BH and VSB lasers. This is consistent with the theoretical unsaturated absorption coefficient of 150 cm^{-1} and 50 cm^{-1} for 1.5 μm and 1.3 μm InGaAsP lasers, respectively.[13]

The saturation of 4-5 μm wavelength emission at about 0.5 I_{th} and the increase above that current in Fig. 2 is interpreted in the same way. In fact, a graph similar to Fig. 5 can be depicted.

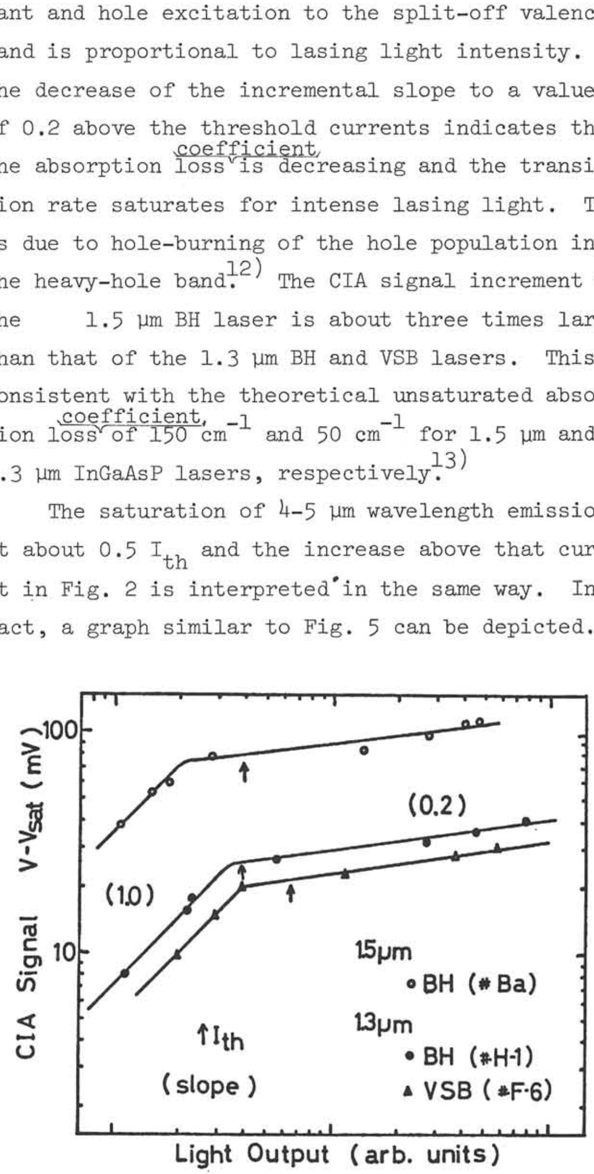

Fig. 5 Double logarithmic plot of CIA signal increment above the saturation (flat region) level vs. 1.3 μm or 1.5 μm light output.

§3. Discussion and Conclusion

The temperature dependence of the threshold current expressed by T_0, given by $I_{th} \sim \exp(T/T_0)$, for the 1.3 μm BH laser (#L-5) is about 50K and the variation of the differential quantum efficiency η_{dif} was negligible in the temperature range below 30°C. But at 50°C, the threshold current increased abruptly and η_{dif} decreased to a tenth. This may be due to the shunt current flowing through the reverse biased InP burying layer. Therefore, the data of the 1.3 μm BH laser (#L-5) at 50°C in Fig. 2 may be slightly modified especially in the high current region. The T_0 value for the 1.5 μm BH laser (#G-1) is about 40K and the variation of η_{dif} is negligible in the measured temperature range. The 4-5 μm emission intensity for this 1.5 μm laser begins to stay constant at about 20 mA for both temperatures of 10°C and 30°C, but the internal absorption loss saturates at the higher current for the higher temperature, resulting in the shift of the flat region to the lower normalized current in Fig. 2. In the low current region, the temperature change of the 4-5 μm light intensity at a fixed current is a factor of 1.5/20°C and 2.6/40°C for the 1.5 μm and the 1.3 μm sample, respectively. If this change is attributed to the change of the Auger recombination rate ($\sim Cn^3$) and if a constant Auger coefficient is assumed,[14] this implies that the carrier density increases by a factor of 1.15 and 1.38 for the respective temperature rise. When the current is kept constant, this leads to the decrease of the radiative recombination coefficient B by a factor of 0.76 and 0.53 for the 20°C and 40°C temperature rise for the 1.5 μm and 1.3 μm lasers, respectively. These values are in reasonable agreement with the reported temperature dependence of $\exp(-\Delta T/77)$,[15] although a possibility of a slight shunt current may vary the quantitative description to some extent.

In conclusion, we have for the first time observed the 4-5 μm emission from the 1.3 μm and 1.5 μm InGaAsP lasers which is attributed to the recombination of holes in the split-off valence band and electrons in the light-hole valence band. The remarkable agreement of the current dependence of the 4-5 μm emission and the CIA signal shows that both phenomena are closely related with the split-off valence band. The main mechanism of these phenomena was estimated to be the CHSH Auger recombination in low current regions and the intervalence band absorption near and above threshold currents. It was shown that the lasers are already superluminescent at about a half of the threshold current and the intervalence band absorption loss coefficient decreases above the threshold current, resulting in a relatively low loss coefficient.[16]

The authors would like to express their thanks to Dr. M. Nakamura, Central Research Lab., Hitachi Co. Ltd., Dr. T. Ikegami and Dr. H. Nagai, Atsugi Electrical Communication Lab., Nippon Telegraph & Telephone Public Corp., and Dr.M. Takusagawa, Fujitsu Lab. Ltd. for kindly supplying the InGaAsP lasers used in the present work. The authors also wish to thank H. Taniguchi for the preparation of the experimental equipment and T. Kawano for assistance with the experiments. This work was partially supported by scientific Research Grant-In-Aid (Special research project: Nano-meter Structure Electronics) from the Ministry of Education, Science and Culture and by a research grant from the Shimazu Science Foundation.

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