Rapid Intensity Degradation in InGaSb/InAlGaSb Quantum Well Lasers

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Abstract

As a factor to limit higher lasing temperature, the rapid lasing intensity degradation in mid-infrared InGaSb/ InAlGaSb quantum well (QW) laser diode has been found and analysed. Due to higher resistance, defects, produced and developed by driving current in p-cladding layer, destroy lattice structure and make the lasing intensity decay. SEM result confirms the defects appeared in p-cladding layer and induced by driving current. Non-radiative recombination induced by defects in the structure is confirmed to result in the optical emission decay at higher temperatures, through the analysis of the electroluminance.

Keywords

Laser Intensity Degradation; Mid-Infrared Laser; Ingasb/Inalgasb Quantum Well; Electroluminance

Introduction

Mid-infrared (2-5 μm) diode laser sources are developed for applications in molecular spectroscopy, optical gas sensors and free space optical communications etc. Except for the QCL/ICL structures (Kim, et al), double heterojunction (Yin, et al) still can't be operated at room temperature at over 3 μm wavelength range. As one of the promising choice, Type-I InGaSb/InAlGaSb quantum well lasers have already reached some success at 3-4 μm spectrum (Nash, et al) and afterwards experimental photoluminance (PL) results suggest that higher lasing temperature is possible (Yin, et al). However, the laser diodes suffered from rapid degradation during the light-current (L-I) test at some temperatures. After the degradation, there was an increase for the laser threshold current at the subsequent test and no lasing found for the higher temperatures. The laser operating temperature depended on lasing degradation temperature, that is, the lower the degradation temperature is, the lower the lasing temperature is. The mechanism to cause degradation in Type-I InGaSb/InAlGaSb quantum well laser structure will be discussed in the paper.

Experimental Results and Analysis

The GaInSb/AlGaInSb QW laser diodes were grown by molecular beam epitaxy at QinetiQ Malvern onto on-axis semi-insulating (001) GaAs substrates. The detail of the laser structure has been described in reference (Nash, et al), where the device configuration ensures no GaAs substrate involving in the electrical conduction. The width of one laser stripe is 10 μm. p-cladding layer depth is 4 μm. The lasing degradation can be found in Fig. 1, where inset shows a typical lasing degradation as a function of time, at the temperature of 150K and current of 200 mA. The later L-I curve at 170K shows no lasing appeared even though the input current was increased to 2A as in Fig. 1. The increase for the laser threshold current after the degradation is in Fig. 2, where 1st means the first L-I curves without the lasing degradation at 10 K and 150 K and 2nd is the L-I curves obtained after lasing degradation.

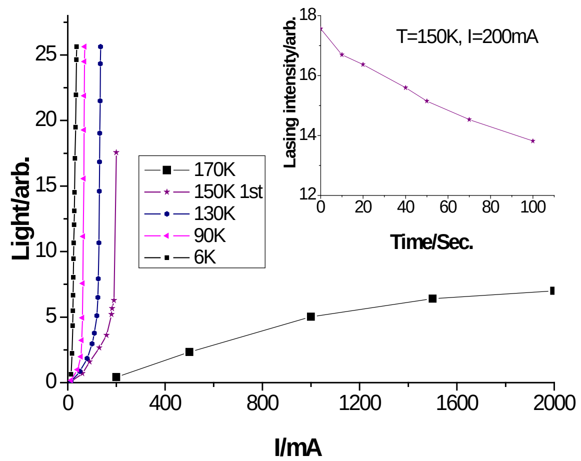

FIG. 1 CURRENT-LIGHT RELATIONSHIPS AT DIFFERENT TEMPERATURES WITH LASER RAPID DEGRADATION AS A FUNCTION OF TIME AT 150K INSET AND NO LASING FOUND AT 170K.

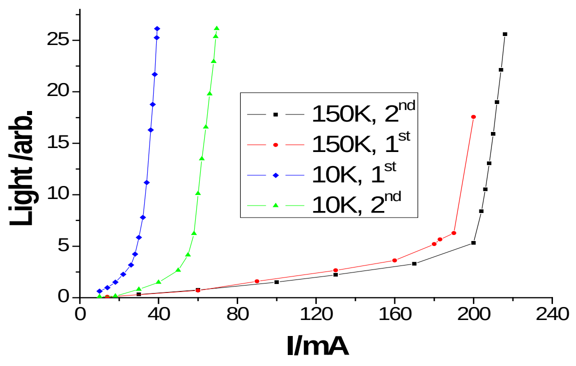

FIG. 2 CURRENT-LIGHT RELATIONSHIPS AT 10K AND 150K, WHERE 1ST IS THE INITIAL TEST WITH DEGRADATION HAPPENED AT 150K AND THE 2ND IS THE REPEATED TEST AFTER LASING DEGRADATION.

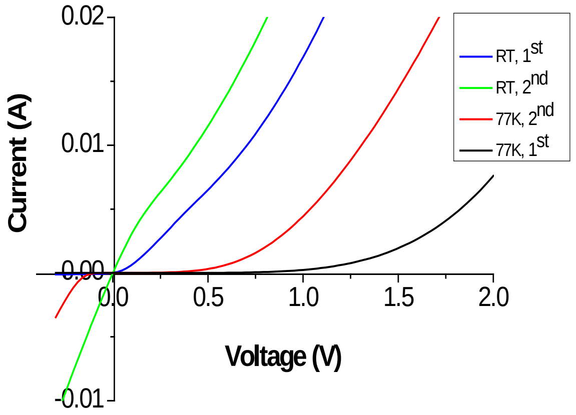

FIG. 3 CURRENT–VOLTAGE (I-V) CHARACTERISTICS BEFORE (1ST TEST) AND AFTER (2ND TEST) LASER DEGRADATION AT ROOM AND LOW (77K) TEMPERATURES

The lasing degradation affects the current-voltage (I-V) characteristic as in Fig. 3, where the first test represents the initial I-V curves (before degradation), and the second test is that after degradation. The series resistance is quite high (~40 Ω at 77 K) in our samples. The device series resistances have been reduced and reverse current leakage increased after degradation.

The limitation of mid-infrared Type-I QW laser diode to operate at room temperatures was usually considered as the strong Auger recombination, due to the narrow band gap alloys in laser active region. Another probability of laser degradation is the facet damage in the QW region because of the high optical density there. However, there is no facet damage found in the QW region from our SEM analysis. Even though the rapid lasing degradation (as the factor to influence the laser operating temperature) could be produced by Auger recombination, the defective non-radiative recombination is also highly possible to make the degradation.

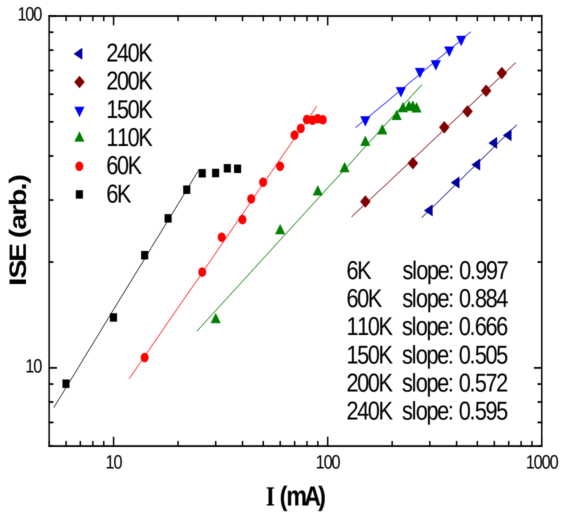

FIG. 4 THE INTEGRATED SPONTANEOUS EMISSION (ISE) AS FUNCTION OF INJECTED CURRENT AT DIFFERENT TEMPERATURES

There are investigations about the laser degradation, resulting from local heating and injected current, both appeared in short wavelength and near infrared spectrum such as in references (Meneghini, et al), (Martin-Martin, et al), where driving current and local heating induced increase of defective non-radiative recombination was discussed, as well as the defect development and propagation (Andrianov, et al). The degradation may happen in separate confinement heterostructure (SCH) layer rather than in the active layer at early stage of the lasing degradation (ITO, et al).

The series resistance in our samples is about ~40 Ω at low temperatures. The high resistance comes mainly from 4 μm p-cladding layer, which could be the source of the local heating and defect extension. To look into the cause of the laser degradation especially if the driving current affected non-radiative recombination defects in our samples, electric-luminance (EL) measurement was used to obtain the spontaneous emission. A special designed holder was applied to collect the optical emission through GaAs substrate and ensure pure spontaneous emission from the device collected.

Fig. 4 shows the spectrum integrated spontaneous emission (ISE) at different temperatures in the laser structure. As the injected current reached the threshold, the intensity of the spontaneous emission was pinned at certain level in Fig. 4 such as at the temperatures of 6, 60 and 110K. Usually, $ISE \propto n^2$ for the optical radiation dominated recombination, where n is the injected carrier concentration. Considering the general equation $I \propto n/\tau = An + Bn^2 + Cn^3$ in high injection, we can obtain,

$$ISE \propto I - AI\tau - C(I\tau)^3 \quad (1)$$

where I is injected current and τ is injected carrier lifetime. A, B and C represent the effects of defects related non-radiative, radiative and Auger recombination coefficient, respectively. So $ISE \propto I$ when radiative emission dominated injected carrier recombination, which is the situation in Fig. 4 for the temperatures of 6 to 60K, where the slope is near one before the lasing threshold. As the temperature rises and driving current is elevated, the gradually reduced slope means that the defects or Auger related non-radiative recombination begins to affect the injected carrier recombination, from Eq. (1). There is the lowest slope at 150K. It is considered as the local heating with defect influence from p-cladding layer as the elevating driving current. The temperature of around 110-150K was not high enough to excite thermal carriers to reduce the resistance in p-cladding layer. So it easily resulted in the current induced local heating defects and increased non-radiative recombination.

Due to lower hole mobility and effective carrier concentration, the high series resistance in p-cladding layer resulted in the local heating and defects with elevated driving current as found in Fig. 5 (b), where two defect spots appeared after laser intensity degradation, near the anode of the laser diode. The spots were induced by driving current, as there were no spots on initially cleaved facet as in Fig. 5(a). The defects destroyed lattice structure of the p-cladding layer, resulted in the degradation of the laser intensity and reduced device series resistance.

The defects might propagate from cladding layer to SCH or QW region as well. The defect development in p-cladding layer was actually observed from inset of Fig. 1, where the defect developing time corresponded to laser degradation time. After the lasing degradation that originated from defect growth and propagation, the series resistance became lower in I-V curves as in Fig. 3, due to the destruction of the crystal structure. Therefore, it's important to increase the doping density and effective carrier concentration to reduce series resistance in InAlGaSb p-cladding layer and finally reach higher lasing temperature.

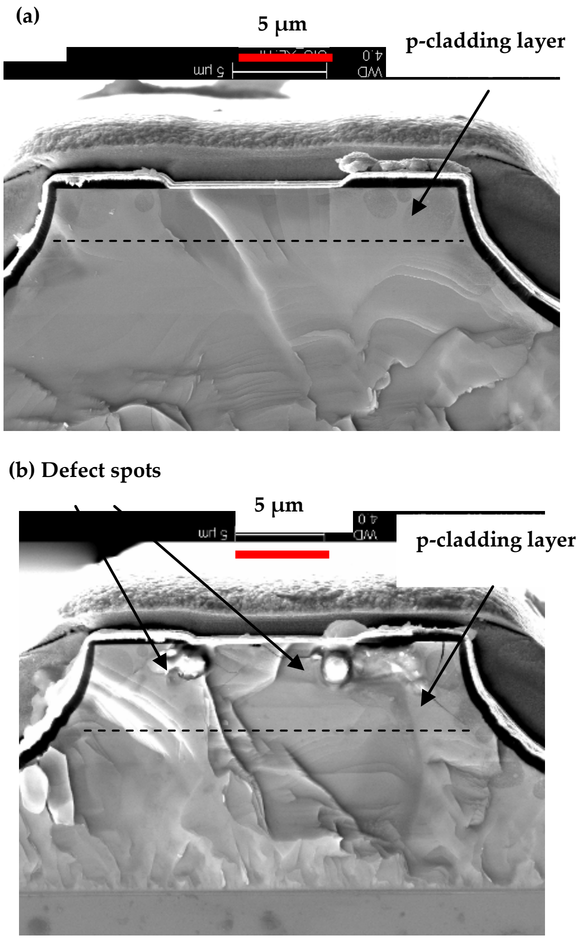

FIG. 5 (a) SEM PROFILE FOR LASER STRUCTURE, WHERE P-CLADDING REGION IS OVER THE DASH LINE. (b) TWO DEFECT SPOTS PRODUCED BY DRIVING CURRENT

Conclusions

In summary, the rapid degradation of laser was found in InGaSb/InAlGaSb type-I QW lasers and it became the factor to limit the laser to operate at higher temperatures. The cause of the laser rapid degradation has been discussed in this paper. The driving current related defect growth and propagation were the source to make the degradation. The analysis suggested that p-cladding layer with the high resistance has resulted in defect growth and propagation to SCH&QW region.

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