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Experimental evidence of nonuniform carrier distribution in multiple-quantum-well laser diodes

Bor-Lin Lee, Ching-Fuh Lin, Jie-Wei Lai and Wei Lin

Carrier distribution in multiple quantum wells is studied. Nonuniform carrier distribution is evidenced by the lasing characteristics of laser diodes with multiple quantum wells of different widths. It is shown that the well sequence significantly influences the threshold current and the characteristic temperature owing to nonuniform carrier distribution.

Carrier distribution in multiple quantum wells (MQWs) is an important issue for understanding the static and dynamic behaviour of QWs [1]. The carrier distribution over MQWs is highly nonuniform and has been studied theoretically [2, 3]. In contrast, less experimental evidence has been presented [4]. In this Letter, we demonstrate the experimental evidence of nonuniform carrier distribution by measuring the lasing characteristics of laser diodes fabricated on substrates with four quantum wells of different widths.

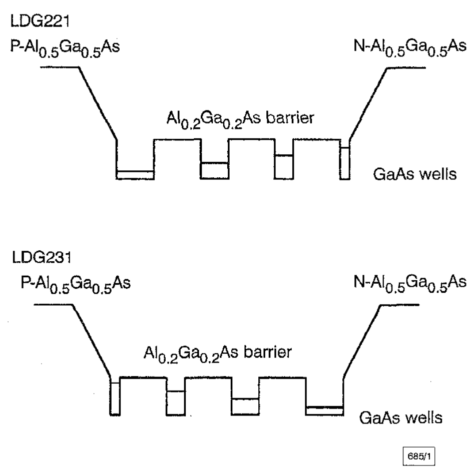

Fig. 1 *Layer structures of four quantum wells of different widths*

The layer structures of the substrates with four quantum wells for the study are shown schematically in Fig. 1. The well widths are 20, 33, 56, and 125Å, respectively. Their $n = 1$ transitions separate for ~50meV, which is large enough to distinguish the corresponding emission spectra. Therefore, the spectrum measurement can be used to identify which well contributes to the emission. Two different sequences of the four wells have been grown by MOCVD. They are termed LDG221 and LDG231, and their sequences are shown in Fig. 1. The LDG231 sample has been used to fabricate superluminescent diodes which demonstrate that all four wells are able to contribute significant emission [5]. Standard processing techniques were used for the device fabrication. Fabry-Perot laser diodes with a 6 μm ridge waveguide were fabricated on the two types of substrate. No coatings were applied to the device facets. The measured devices are all 700μm long.

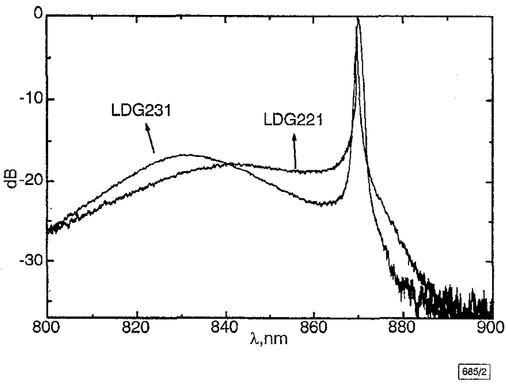

Fig. 2 *Measured spectra of laser diodes*

Fig. 2 shows the measured spectra of the fabricated Fabry-Perot laser diodes. The variation of the lasing wavelength with temperature is also shown in Table 1. In spite of the different sequences of the four wells, they both oscillate at the wavelength around 870 nm, which corresponds to the emission energy of the 125Å well. Because emissions due to the narrow wells always have a larger energy than the separation energy of the first quantised states in the conduction and the valence bands of the widest well, they could be absorbed by the widest well. Consequently, the emission of the widest well experiences the least loss and oscillation is most likely to occur at the corresponding transition wavelength.

Table 1: Variation of lasing wavelength with temperature

λ °C	LDG221	LDG231
20	867.3	867.5
30	869.7	870.5
40	871.8	873.3
50	874.8	875.7

Although the emission wavelength is the same, the threshold currents of the laser diodes fabricated from the two samples are different. Those fabricated on the LDG221 substrate have a threshold current ~30mA, while those fabricated on the LDG231 substrate have a threshold current almost twice this. The reason for this is discussed briefly in the following. The threshold current of a laser diode is determined by its material gain, confinement factor, internal loss, and mirror loss. Because the two samples have the same separate confinement heterostructures and waveguide structures, their internal loss, mirror loss, and confinement factor are approximately the same. This indicates that the difference in threshold comes from the different material gain at the same injection condition. The material gain depends on temperature, well/barrier structure, and carrier density in the QW [6]. Therefore, we believe that the carrier distribution among the four wells is different for the two samples. Because the LDG221 sample has its 125Å well closest to the *p*-cladding layer, it has more holes accumulated in this wide well than the LDG231 sample has at the same injection current. Conversely, the LDG231 sample has the 125Å well closest to the *n*-cladding layer, so it has more electrons accumulated in this well than does the LDG221 sample. The experimental measurements indicate that the distribution of holes is the dominant factor. As a result, with the same injected current, LDG221 devices have more gain for the wavelength corresponding to the 125Å well than do the LDG231 devices, leading to a significantly reduced threshold current for the LDG221 devices.

The dominant role played by the holes is further evidenced by the measurement of the temperature dependence of the threshold current. The characteristic temperatures of LDG231 devices and LDG221 devices are 50 and 100K, respectively. As is clearly shown in Fig. 3, the LDG231 devices suffer a more serious temperature effect. As the temperature increases, the mean free path of unbounded carriers, especially the holes [4], is reduced. This means that the holes in the LDG231 sample have more difficulty in passing through other wells to reach the 125Å well, leading to significantly decreased hole concentration in this well at the same injection current. Consequently, the material gain of this sample is significantly reduced owing to the temperature rise, and hence more temperature effect is experienced.

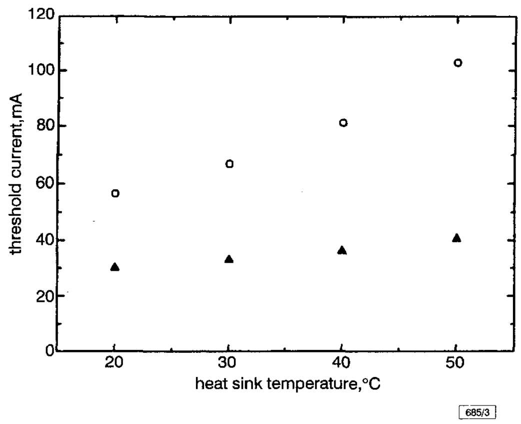

Fig. 3 *Measured threshold current against temperature*
○ LDG231
▲ LDG221

In conclusion, the lasing characteristics of semiconductor lasers are experimentally found to depend on the sequence of multiple quantum wells with different widths. The threshold current of laser diodes with the widest well closest to the *p*-cladding layer is only half that of laser diodes with the opposite well sequence. In addition, the former devices have a characteristic temperature twice that of the latter devices. These observations indicate that carrier distribution among the multiple quantum wells is not uniform and that hole distribution plays the dominant role in determining lasing characteristics.

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High-temperature operation of 1.3μm AlGaInAs strained multiple quantum well lasers

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High-temperature operation of 1.3μm AlGaInAs/InP strained multiple quantum well lasers is demonstrated. An excellent CW characteristic temperature of 111K was obtained between 20 and 80°C and a record high operating temperature of 210°C was achieved with a 700μm long laser under pulse excitation. Power reductions at a constant current with increasing temperature were also evaluated at 80°C to be –1.27 and –1.67dB under pulse and CW excitations, respectively.

Introduction: 1.3μm semiconductor lasers are important light sources for application to subscriber loop networks and optical interconnection systems and are required to operate over a wide temperature range without thermoelectric devices. To achieve this, electron overflow from active layers must be suppressed at high temperatures. AlGaInAs/InP systems, which have a larger conduction band offset ($\Delta E_c = 0.72\ \Delta E_g$) than conventional GaInAsP/InP systems ($\Delta E_c = 0.4\ \Delta E_g$), have been proposed to reduce the electron overflow [1], and excellent temperature characteristics of AlGaInAs/InP lasers have been demonstrated [2, 3]. Recently, we have reported AlGaInAs/InP lasers with p-AlInAs electron stopper layers (ESLs) introduced between the multiple quantum well (MQW) active and p-type separate confinement heterostructure (SCH) layers to further suppress electron overflow from MQW to SCH layers [4]. The characteristic temperatures of threshold current and slope efficiency were found to be improved by ESLs. The improvement was more remarkable at higher temperatures and the maximum operating temperature of lasers with ESL was found to be higher than that of lasers without ESL.

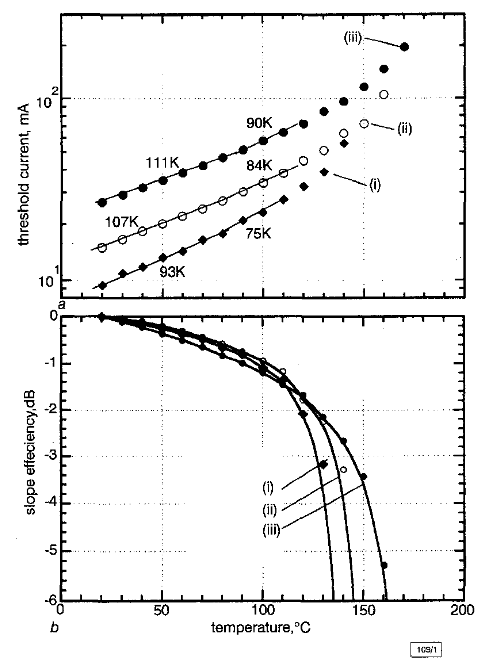

Fig. 1 *Temperature dependence of threshold current and slope efficiency for lasers with various cavity lengths under CW excitation*

a Threshold current
b Slope efficiency
(i) L = 200μm
(ii) L = 350μm
(iii) L = 700μm
CW, 28–95%

In this Letter, we report the high-temperature characteristics of 1.3μm AlGaInAs/InP strained MQW lasers with the p-AlInAs ESL. Excellent characteristic temperatures of 111K between 20 and 80°C and 90K between 80 and 110°C were achieved. CW laser operation was obtained up to 170°C and a record high operating temperature of 210°C was achieved under pulse excitation.