InGaAsP/InP laser diodes/superluminescent diodes with nonidentical quantum wells

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Abstract - Novel behavior of laser diodes (LDs) and superluminescent diodes (SLDs) fabricated on substrates with nonidentical quantum wells has been discovered. Mirror-imaged nonidentical quantum well (QW) lasers/superluminescent diodes have been designed, fabricated, and measured. Nonuniform carrier distribution inside multiple quantum wells is further verified experimentally. Measured characteristics also show that electrons, instead of holes, are the dominant carrier affecting carrier distribution. The sequence of the nonidentical QW is also shown to have significant influence on device characteristics, showing very different carrier distribution in each sequence.

A. Introduction

Multiple-quantum-well (MQW) semiconductor lasers have the advantages of higher differential gain, wider modulation bandwidth, and better temperature characteristics than bulk-material semiconductor lasers. These advantages make MQW lasers attractive to all fields of applications, including optical communication. Due to the step-like density of states of MQW structures, MQW lasers were predicted to have improved properties, e.g., high-frequency response, compared to bulk lasers [1]. However, because of the quantization nature of QWs along the epitaxial axis, complicated carrier dynamics are involved therein [2]. Contemporary models describing carrier dynamics involve carrier diffusion/drift across the unquantized 3D structure, and the processes by which carriers are captured into and escape from the QWs. These processes cause transport delays, and degrade the dynamic properties of MQW lasers. Thus designing such MQW structures is not straightforward. Carrier dynamics need to be understood in advance. Calculations using rate equations [3] have shown that the carrier density inside the MQW structure is not uniform, and has been verified experimentally [4]. This work reports the study on laser diodes (LDs)/ superluminescent diodes (SLDs) with nonidentical InGaAsP QWs grown on InP substrates. Nonuniform carrier distribution inside MQW is further evidenced. Other types of novel behavior have been discovered.

When MQW lasers are forward biased, electrons inject from n-cladding layer and holes injected from the opposite direction, causing a nonuniform carrier distribution. Studies have defined the "dominant carrier" as the carrier from the side that the carrier distribution density is higher and so determines the carrier distribution. Past researches suggested holes as the dominant carrier due to the larger density of states in the valence band and hence shorter capture time into QW. However, this work shows the opposite result: namely that electrons are the dominant carriers.

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B. Experiment

B.1 Mirror-Image nonidentical QW group I

Substrates with four nonidentical $In_{0.56}Ga_{0.44}As_{0.95}P_{0.05}$ QWs bounded by 150Å $In_{0.79}Ga_{0.21}As_{0.45}P_{0.55}$ barrier were used to fabricate LDs. The widths of the four QWs are 22Å, 40Å, 60Å, and 150Å. Substrate 05112 and 05111 have the 150Å well nearest to the n-cladding and p-cladding, respectively, while other wells are placed in the order according to their widths.

The nonidentical MQW structures are grown on InP substrate with lattice-matched condition by MOCVD. The grown nonidentical MQW structures are then used to fabricate ridge-waveguide laser diodes (LDs) by standard processing procedures. The ridge waveguide was created by ECR- RIE and etching was stopped at ~100nm above the SCH layer. The devices are about 500μm long.

The lasing characteristics of fabricated LDs are measured in temperatures varying from 20°C to 55°C. Under room temperature the 05111 LDs have the lasing wavelength at 1501.36nm and the 05112 LDs have the lasing wavelength at 1483.68nm. The experiments show that 05112 LDs have the threshold current I_{th} only half of 05111 LDs, as shown in Fig. 1, although both types of LDs have their lasing wavelength contributed from the 150Å QW. This indicates that more carriers are trapped in the QW near the n-cladding, as schematically shown in Fig. 2. Therefore, electrons are the dominant carriers controlling the nonuniform carrier distribution among MQWs, in contrast to the common concept that holes are the dominant ones. The electron-dominant behavior also causes 05112 LDs to have higher differential quantum efficiency (η) than 05111 LDs. Nonetheless; η of 05111 is less reduced by temperature (*T*) than η of 05112. The extrapolations from η vs. *T* plots of 05111 and 05112meet at *T*=143°C. This implies that, for *T* > 143°C, carrier escape plays a much more important role on the carrier distribution than other factors like the well sequence.

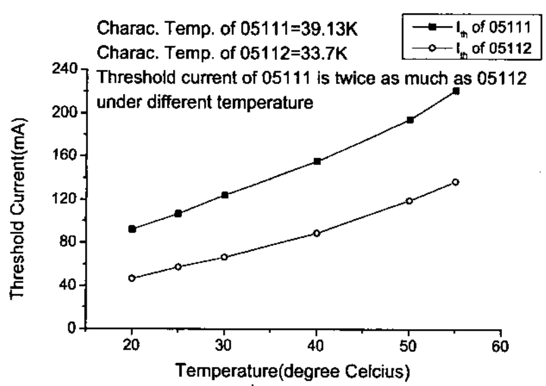

Fig. 1. I_{th} vs. temperature of 05111/05112.

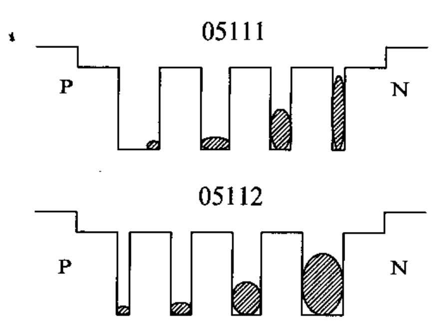

Fig. 2. Carrier distribution inside MQWs of 05111/05112 (Schematically).

B.2 Mirror-Image nonidentical MQW group II

In the second experiment, substrates with three 60Å $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ QWs (designed approximately for lasing wavelength λ=1.3μm) and two 87Å $In_{0.53}Ga_{0.47}As$ QWs (designed approximately for λ=1.55μm), bounded by 150Å $In_{0.86}Ga_{0.14}As_{0.3}P_{0.7}$ barrier, were used to fabricate LDs and SLDs. Substrates 04291 and 04292 have the three 60Å QWs near the p-cladding and the n-cladding, respectively. Ridge-waveguide LDs were fabricated with the same procedure as above, while SLDs are fabricated with bend-waveguide structure, and the device lengths are about 500μm. The sequence of QWs again has a very important influence on the SLDs and LDs. For SLDs, substrate 04292 has the emission mainly contributed from the 60Å QWs, while substrate 04291 has emission contributed from both 60Å and 87Å QWs, thus demonstrating very broadband emission, covering from <1.3μm (by 60Å QWs) to >1.55μm (by 87Å QWs).

Their spectra measured under different current levels are shown in Fig. 3 and Fig. 4, respectively. For LDs, substrate 04292 and 04291 have the lasing wavelength at around 1415nm and around 1500nm, respectively, showing that QWs near the n-cladding contribute more to emission. 04292 LDs also demonstrate novel wavelength switching that can be controlled by temperature variation of 5°C. Furthermore, the lasing wavelengths of 04292 and 04291 LDs could randomly occur in a spectral range of about 20nm when the bias current is at the same level leading to a very flat gain plateau profile. The lasing spectra are shown in Fig. 5 and Fig. 6. The reason is probably because the start-up noise significantly influences the final lasing wavelength, like chaotic behaviors, when the LDs gain profile is very flat at some current level.

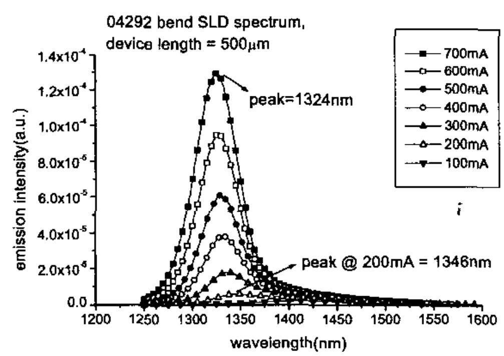

Fig. 3 Spectra of 04292 under different current

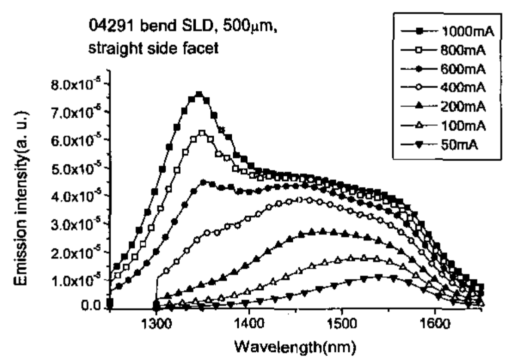

Fig. 4 Spectra of 04291 under different current

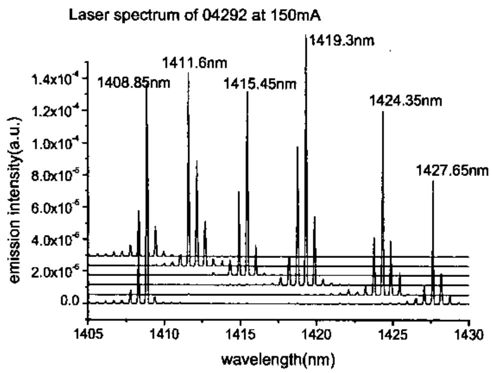

Fig. 5 Lasing spectra of 04292 under same current.

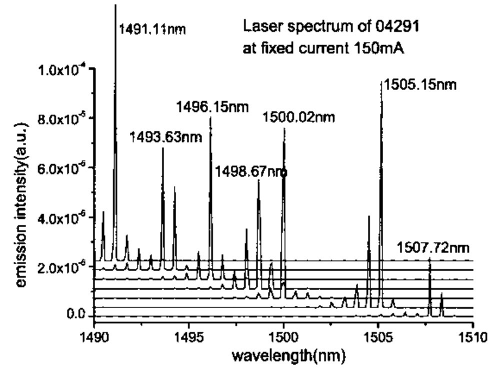

Fig. 6 Lasing spectra of 04292 under same current

C. Discussion

The emission characteristics shown above are apparently related to the sequential capture of carriers into the MQWs. The sequence of MQWs influences the carrier distribution, so the devices have characteristics corresponding to the carrier density in each well. From the above experiments, electrons being the dominant carrier implies longer delay time for holes than for electrons to be captured into QW. The reason may be due to the length of the separate confinement heterostructure. The above experiments show that LDs and SLDs with nonidentical QWs involve more complex physics than those with conventional QWs of the same widths. Thus more functions might be achieved using nonidentical MQWs.

References

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