Quantum Well Laser Diodes With slightly-doped tunnel junction

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***Abstract*—We experimentally investigate the electrical and optical characteristics of conventional quantum well laser diodes and the quantum well laser diodes with slightly-doped tunnel junction N++GaAs/undoped-GaAs. The results show that the slightly-doped tunnel junction give significant role on the laser diodes performances in the InGaAs/GaAs quantum well material system. The TJ LD has a internal quantum efficiency of 21% and the loss is 6.9 cm^{-1}, the current threshold is 35 mA, both the lasers are operating at 1.06 µm, but the slightly-doped tunnel junction diode show nonlinear S-shaped current–voltage and broadband lasing characteristics. The results may also lead to the realization of more applications.**

Keywords—Tunneling; Multiple quantum well; Broadband; Semiconductor lasers

I. INTRODUCTION

Semiconductor laser diodes (LDs) are used at present in a variety of fields in science and technology. Tunnel junction, which was proposed by Esaki [1], has been widely used in many semiconductor LDs for different applications. Overview the tunnel junction semiconductor lasers, there are mainly three different kinds of structures: First, reverse-biased tunnel junctions comprised of heavily doped p-type and n-type layers are located between adjacent LDs provides good electric contact [2]. This kind of semiconductor lasers can enhance the quantum efficiency and output optical power of lasers. The principle of these devices is to inject one electron-hole pair into the active regions to produce N times electron-hole pairs through cascaded tunnel junctions, where N is the number of the active regions. The internal quantum efficiency of this cascaded lasers can be much larger than unity while for conventional lasers. Second, dual-wavelength lasers based on the bipolar cascade lasers (BCL) with a similar structure also have been demonstrated [3]. The dual-wavelength BCL is composed of two different active regions with different multi-quantum-wells (MQWs) and the active regions are connected by a very thin reverse-biased tunnel junction (TJ). The TJ requires materials with high n-type and p-type doping levels, low dopant diffusion, and large and gaps to avoid absorption. Third, the forward-biased tunnel junction with a high doped n-type and p-type layers are located on the top of LD [4],[5], the negative differential resistance (NDR) of the TJ have been used in optical bistable devices, which are the key components in future optical switching and computing systems. The principle of these devices is the tunnel diode section provides a differential negative resistance which induces an electrically bistable characteristic when connected in series with the laser section and an external load. Thus the coherent light output from the device displays a negative differential optical response and bistable effects in response to an applied voltage.

In these tunnel junctions, the high-doping of the layers composing TJ plays a crucial role for optimizing and engineering device properties. Recently the slightly-doped tunnel junction semiconductor lasers have been reported to achieve the broadband stimulated emission [6],[7]. However, the mechanisms behind these principles are not revealed yet, furthermore, how the slightly-doped tunnel junction determine the laser performance also unrevealed in the reported literatures. In this letter, we report GaAs/InGaAs quantum well lasers with slightly-doped p-n+ GaAs-GaAs reverse-biased tunnel junctions located below the upper cladding layer. The electronical and optical properties are investigated compared with conventional QW lasers.

II. DEVICE STRUCTURE AND FABRICATION

Samples used in this study were grown on a heavily n-doped GaAs substrate via Metal Organic Chemical Vapor Deposition (MOCVD) using only one step growth. Fig. 1. (a) and (b) schematically depict the structures of the conventional and the slightly-doped TJ LDs, respectively. For the conventional LD, we first deposited a 400-nm-thick GaAs buffer layer , a 1.8-µm-thick Si-doped n-AlGaAs cladding layer and a 100-nm-thick AlGaAs and a 400-nm-thick GaAs separate confinement heterostructure (SCH) layer. Subsequently, a MQW active region consists of 2 pairs of 5-nm-thick InGaAs well layers and 15-nm-thick GaAs barrier layers was deposited. A 100-nm-thick AlGaAs and a 400-nm-thick GaAs SCH layer, a 1800-nm-thick p-AlGaAs cladding layer and a 300-nm-thick p+-GaAs contact layer were then grown on top of the MQW active region, as shown in Fig. 1. (a). For the slightly-doped TJ LDs, we deposited the TJ structure on top of the conventional LD. It should be noted that the growth condition for the second LD structure is identical to that for the conventional LD. On the other hand, the TJ structure consists of a 10-nm-thick n++-GaAs layer, a 8-nm-thick undoped GaAs layer, as shown in Fig. 1. (c). After the growth, Standard Fabry-Perot laser procedures were then used to fabricate a ridge waveguide with a width of 4 µm and a depth of 2.2 µm. A silicon dioxide insulating layer was grown by Plasma-Enhanced Chemical Vapor Deposition (PECVD), Then Ti/Au metal p-contacts and Au/Ge/Ni n-contacts were deposited. Finally, the wafers were cleaved into L 300 µm × W 200 µm individual chips with both facets left uncoated (as-cleaved).

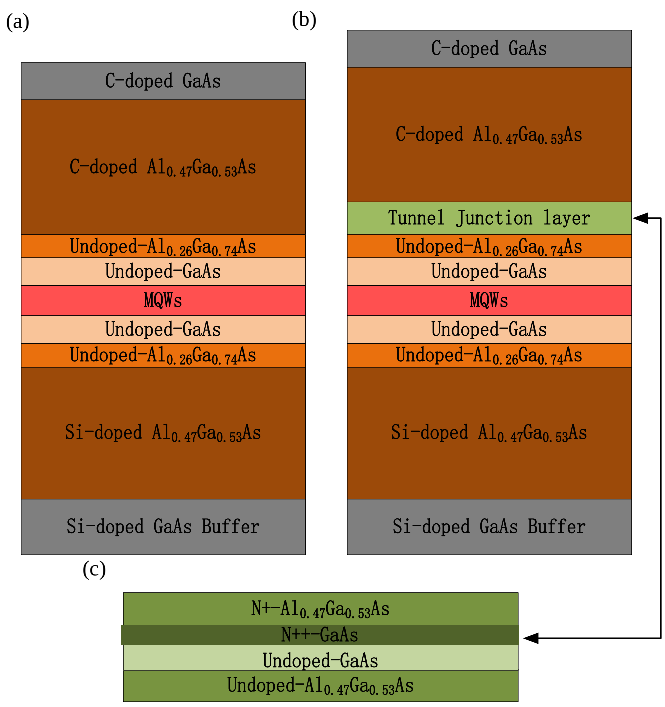

Fig. 1. Schematic diagrams of (a) conventional LD, (b) TJ LD and (c) Slightly-doped TJ structure used in this study

III. RESULTS AND DISCUSSION

Current-Voltage (I-V) characteristics measured from these devices were plotted in Fig. 2. It was found that the conventional LD has a normal p-n diode characteristic with the threshold voltage of 1.2 V. But for the TJ LD, it shows a nonlinear S-shape I-V characteristic, which include low-current OFF state, high-current ON state and negative differential resistance region. The measured switching voltage and current are 9.5 V and 3 mA, respectively. The holding voltage and current are 3.9 V and 7.8 mA, respectively. This kind of thyristor switching devices with lasing properties also dedicated to the optical switching application [8],[9]. The I–V characteristics can be improved by optimizing the thickness of the center layers and the doping concentration of slightly-doped tunnel junction layers.

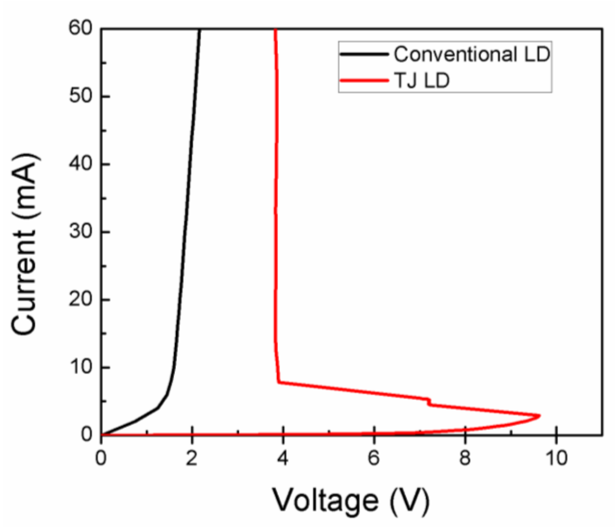

Fig. 2. I-V characteristics measured from the two fabricated LDs

Fig. 3. shows L-I characteristics measured from the two fabricated LDs. With an output power of 20 mW, it was found that injection currents for the the conventional LD and TJ LD were 82 mA and 172 mA, respectively. Besides, the current threshold of the TJ LD is 36 mA, which is three times higher than conventional LD. This is because the slightly-doped TJ increased the barrier width. As a consequence, the electron tunneling probability reduces and the effective resistivity of the TJ increases. High-resistive layers can be the reason for a strong lateral current spreading in the laser and, as a consequence, lower differential quantum efficiency and higher threshold currents [10].

In a symmetric Fabry–Perot cavity, both the mirror losses are identical and depends on laser length and facet power reflectivity, which leads to the common expression

$$\frac{1}{\eta_D} = \frac{1}{\eta_i} + \frac{\alpha_i}{\eta_i \, ln(1/R)} L \quad (1)$$

Where η_d is the differential quantum efficiency, η_d is the internal quantum efficiency, L is the cavity length, R is the facet reflectivity. This equation gives a linear dependence and it is widely used to determine the loss parameters and from measurements with different laser lengths [11]. The results of the TJ LD and the conventional LD are shown in Fig. 4. Conventional LD internal quantum efficiency is 87.3% and the loss is 0.85 cm^{-1}. TJ LD internal quantum efficiency is 21% and the loss is 6.9 cm^{-1}. The low internal quantum efficiency and the high loss lead to the low output power and the high current threshold.

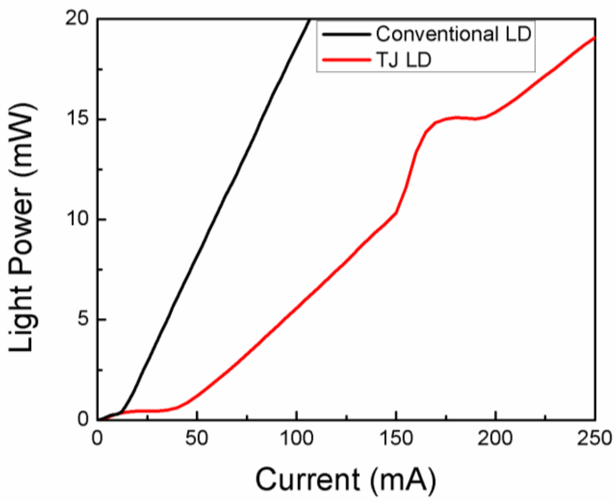

Fig. 3. L-I characteristics measured from the two fabricated LDs

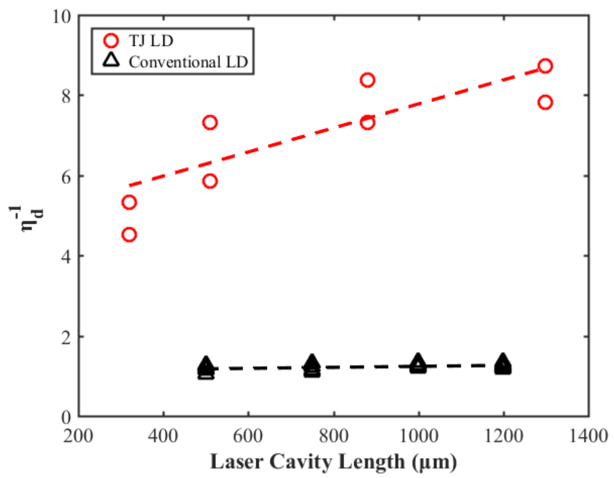

Fig. 4. Inverse slope efficiency $1/\eta_d$ versus laser length L as measured. Linear regression results are given as lines together with the parameters of (1).

Fig. 5. (a) and (b) show electroluminescence (EL) spectra measured from the conventional LD and TJ LD, respectively. It can be seen that EL peaks occurred indeed at around 1060 nm for both LDs, as designed. It was also found that the peak wavelength of the conventional LD shifts from 1055 nm to 1058 nm with increasing injection current, which hints that wavelength tenability can be easily achieved not only through a temperature change, but also by adjusting the operation current. But for the TJ LD, it shows the broadband emission characteristic, as the injection level is increased to 4.5 × Ith, the spectrum broadens toward a longer wavelength and gives a 15 nm broad spectrum. This is because the lasing dynamics reflects the current dynamics formed as a result of complex nonlinear couplings within the laser-thyristor heterostructure [12], [13]. The spectrum can be further broad with the increased injection current [14].

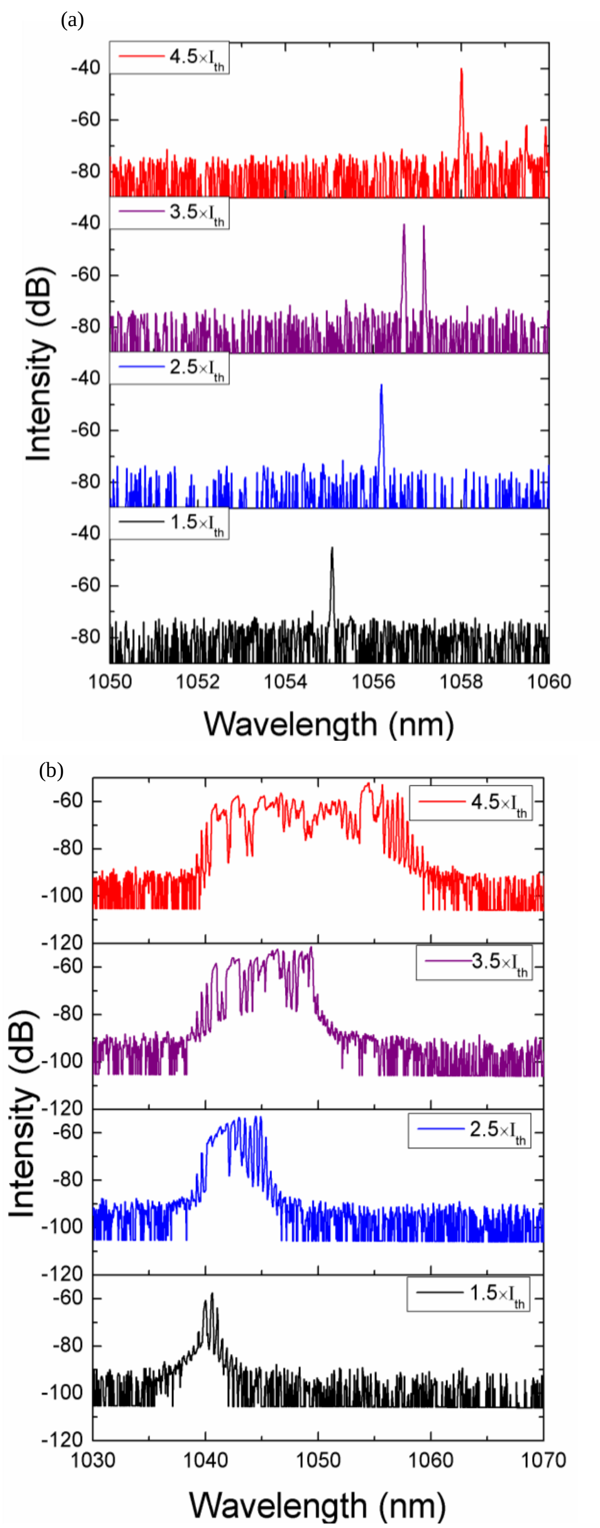

Fig. 5. EL spectra measured from (a) conventional LD, (b) TJ LD

IV. CONCLUSIONS

In summary, we experimentally investigate the electrical and optical characteristics of conventional quantum well laser diodes and the quantum well laser diodes with slightly-doped tunnel junction N++GaAs/undoped-GaAs. The TJ LD has a internal quantum efficiency of 21% and the loss is 6.9 cm^{-1}, the current threshold is 35 mA, both the lasers are operating at 1.06 μm. The results show that the slightly-doped tunnel junction plays a critical role in the laser performances. The results may also lead to the realization of more applications, such as mode locking with ultra-short pulse generation, biomedical imaging, broad wavelength tenability, and multiwavelengths generation.

REFERENCES

[1] Esaki, "New Phenomenon in Narrow Germanium p-n Junctions," Physical Review, vol. 109, no. 2, pp. 603-604, 1958.

[2] J. P. v. d. Ziel, and W. T. Tsang, "Integrated multilayer GaAs lasers separated by tunnel junctions," Applied Physics Letters, vol. 41, no. 6, pp. 499-501, 1982.

[3] J. Yan, J. Cai, G. Ru, X. Yu, J. Fan, and F.-S. Choa, "InGaAsP-InP dual-wavelength bipolar cascade lasers," IEEE photonics technology letters, vol. 18, no. 16, pp. 1777-1779, 2006.

[4] J. Mi, H. Yu, H. Wang, S. Tan, W. Chen, Y. Ding, and J. Pan, "A GaAs-Based Hybrid Integration of a Tunneling Diode and a 1060-nm Semiconductor Laser," IEEE Photonics Technology Letters, vol. 27, no. 2, pp. 169-172, 2015.

[5] I. Gravé, S. C. Kan, G. Griffel, S. W. Wu, A. Sa'ar, and A. Yariv, "Monolithic integration of a resonant tunneling diode and a quantum well semiconductor laser," Applied Physics Letters, vol. 58, no. 2, pp. 110-112, 1991.

[6] H. Wang, X. Zhou, H. Yu, J. Mi, J. Wang, J. Bian, Y. Ding, W. Chen, W. Wang, and J. Pan, "Ultrabroad stimulated emission from quantum well laser," Applied Physics Letters, vol. 104, no. 25, pp. 251101, 2014.

[7] Wang H., H. Yu, X. Zhou, Q. Kan, L. Yuan, W. Chen, W. Wang, Y. Ding, and J. Pan, "High-power InGaAs/GaAs quantum-well laser with enhanced broad spectrum of stimulated emission," Applied Physics Letters, vol. 105, no. 14, pp. 141101, 2014/10/06, 2014.

[8] G. W. Taylor, and H. Opper, "A New Digital OptoElectronic Switch (DOES) Laser," IEEE Journal of Quantum Electronics, vol. 53, no. 3, pp. 1-10, 2017.

[9] Wang, H., Mi, J., Zhou, X., Meriggi, L., Steer, M., Cui, B., Chen, W., Pan, J., and Ding, Y.: "1.06-μm InGaAs/GaAs multiple-quantum-well optical thyristor lasers with a PiNiN structure", Opt. Lett, 38, (22), pp. 4868-4871 ,2013.

[10] Liu, H. Y., S. L. Liew, T. Badcock, D. J. Mowbray, M. S. Skolnick, S. K. Ray, T. L. Choi et al. "p-doped 1.3 μ m In As⁄Ga As quantum-dot laser with a low threshold current density and high differential efficiency." Applied Physics Letters 89, no. 7. pp.073113. 2006.

[11] H. Kressel and J. K. Butler, Semiconductor Lasers and Heterojunction LEDs. New York: Academic, 1977.

[12] H. Wang, J. Mi, X. Zhou, L. Meriggi, M. Steer, B. Cui, W. Chen, J. Pan, and Y. Ding, "1.06-μm InGaAs/GaAs multiple-quantum-well optical thyristor lasers with a PiNiN structure," Optics Letters, vol. 38, no. 22, pp. 4868-4871, 2013.

[13] Slipchenko, S. O., A. A. Podoskin, O. S. Soboleva, N. A. Pikhtin, T. A. Bagaev, M. A. Ladugin, A. A. Marmalyuk, V. A. Simakov, and I. S. Tarasov. "Effect of the spatial current dynamics on radiative characteristics of high-power lasers-thyristors based on AlGaAs/GaAs heterostructures." Journal of Applied Physics, vol 121, no. 5 , pp. 054502. 2017.

[14] Pan, Jiaoqing, et al. "1060nm high-power broadband InGaAs/GaAs quantum well thyristor-laser." Optical Communications and Networks (ICOCN), 2015 14th International Conference on. IEEE, pp. 1-3, 2015.