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Comparisons of InP/InGaAlAs and InAlAs/InGaAlAs distributed Bragg reflectors grown by metalorganic chemical vapor deposition

T.C. Lu, J.Y. Tsai, H.C. Kuo, S.C. Wang*

Institute of Electro-Optical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 30050, Taiwan, ROC

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Abstract

Long wavelength vertical cavity surface emitting lasers (VCSELs) are considered the best candidates for the low cost reliable light emitters in fiber communications. The low refractive index contrast in the conventional InP-based lattice-matched distributed Bragg reflectors (DBRs), InP/InGaAsP, impeded the development of 1.3–1.5 μm VCSELs. However, the monolithic InP-based lattice-matched DBRs are still most attractive and desirable. The InP/InGaAlAs and InAlAs/InGaAlAs DBRs with larger refractive index contrast than the conventional InP/InGaAsP DBRs have been demonstrated recently. In this report, we compare these two material systems in terms of optical and electrical properties of DBRs. We found the InP/InGaAlAs DBRs have better electrical and optical properties, while the InAlAs/InGaAlAs DBRs have much lower growth complexity.

Keywords: Metalorganic chemical vapor deposition; Distributed Bragg reflectors

1. Introduction

Long wavelength (1.3–1.5 μm) vertical cavity surface emitting lasers (VCSELs) are very attractive light sources for fiber communications due to the advantages of single longitudinal mode, small divergence circular emission beam profile, low power consumption and low cost reliable productions. However, the lack of high refractive index contrast materials for the distributed Bragg reflectors (DBRs) makes the development of long wavelength VCSELs lagging behind the short wavelength (0.78–0.98 μm) VCSELs. In the past few years, high performance long wavelength VCSELs [1,2] were demonstrated using wafer fusion technique, which integrated the InP-based active layers and GaAs-based DBRs together. But the capability of mass production could be an issue. Recently, the InGaNAs 1.3 μm VCSELs grown on GaAs substrates have been demonstrated with excellent characteristics [3,4]. However, to extend the InGaNAs gain to beyond 1.5 μm is still rather difficult.

Monolithically grown DBRs lattice-matched to InP substrates continues to attract interests due to the existing highly efficient InGaAsP and InGaAlAs gain materials with the wavelength window covering from 1.3 to 1.8 μm. The Sb-based DBRs with large refractive index contrasts of Δn ranging from 0.43 to 0.44 have been successfully applied in the VCSEL structures [5,6]. However, these DBRs have drawbacks such as low thermal conductivity and relatively high growth complexity. The conventional InP-based lattice-matched InP/InGaAsP DBR has the problem of the small refractive index contrast ($\Delta n = 0.27$ for InP/InGaAsP) that requires a larger number of DBR pairs to obtain high reflectivity. In addition, the conventional DBRs not only increase the penetration depth causing more absorption, but also create the heat dissipation problem.

Recently, the DBRs based on relatively large refractive index contrast material combinations of InP/InGaAlAs ($\Delta n = 0.34$) and InAlAs/InGaAlAs ($\Delta n = 0.3$) have been demonstrated [7–10]. However, the systematic comparisons of these two material combinations have not been reported. In this study, we used the low pressure metalorganic chemical vapor deposition (MOCVD) system to grow the InP/InGaAlAs and InAlAs/InGaAlAs DBRs. We compared these two material systems in terms of electrical and op-

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* Corresponding author. Tel.: +886-3-5712121x56320; fax: +886-3-5716631.

E-mail address: scwang@cc.nctu.edu.tw (S.C. Wang).

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tical properties of DBRs. In addition, due to the different group V-based materials of InP and InGaAlAs, the epitaxial growth technique and the complexity will also be discussed. We found that the InP/InGaAlAs DBRs have better optical and electrical properties, while the InAlAs/InGaAlAs DBRs have much lower growth complexity.

2. Experimental procedure

All DBR structures were grown in a vertical-type low pressure MOCVD system with a rotating disk. The disk rotated at 900 rounds per minute to maintain the laminar gas flow. The growth pressure was 9.33 kPa. The growth temperature was 625 °C. V/III ratio was 150 for InP and 200 for InGaAlAs. The growth rate was 36.5 and 35 nm/min for InP and InGaAlAs, respectively. The alkyl sources were trimethylindium, trimethylgallium, and trimethylaluminum, and the group V gases were AsH_3 and PH_3. The carrier gas was hydrogen. Si_2H_6 was used as the precursor of the n-type dopant. The epitaxial layers were all grown on n-type (1 0 0)InP substrates. For the growth of InP/InGaAlAs DBRs, we adapted the growth interruption technique we established earlier [11] and chose the interruption time t_p of 0.3 min to make compromises between the total growth time, the amount of source usage and the required high reflectivity. As for the growth of the InAlAs/InGaAlAs DBRs, the epitaxial layers of InAlAs/InGaAlAs were directly switched since both materials have the same group V source.

The thickness of each layer and the vertical compositional profiles were investigated by the field emission scanning electron microscope (SEM) and the secondary ion mass spectrometry (SIMS). The high-resolution transmission electron microscope (TEM) was used to investigate the abruptness of the interface. The current–voltage (*I*–*V*) measurement was used to determine the resistance of the n-type doped DBRs. The spectrometer was used to determine the reflectivity of the DBRs. The reflectivity of the Au film was used as the reference.

3. Results and discussion

The DBRs with seven pairs n-type InP/InGaAlAs and InAlAs/InGaAlAs designed for 1.55 μm VCSELs were first grown and investigated. The quarter-wavelength thickness of InP, InAlAs and InGaAlAs was 122, 121 and 110 nm, respectively. To avoid the absorption of DBRs while the operating wavelength was 1.55 μm, the lattice-matched $In_{0.53}Ga_{0.39}Al_{0.08}As$ was used with a band gap emission wavelength of 1.42 μm. The as-grown wafers were dry etched roughly 1.8 μm down to the n-type InP substrate to form a round mesa with the diameter of 50 μm. The periphery of the mesa was then passivated by SiN_x. After the thinning of the n-type InP substrate, the AuGe/Ni/Au contacts were deposited on the both sides of the wafers.

Fig. 1 (a) and (b) show the interface conditions of the InP/InGaAlAs DBRs examined by TEM for two different

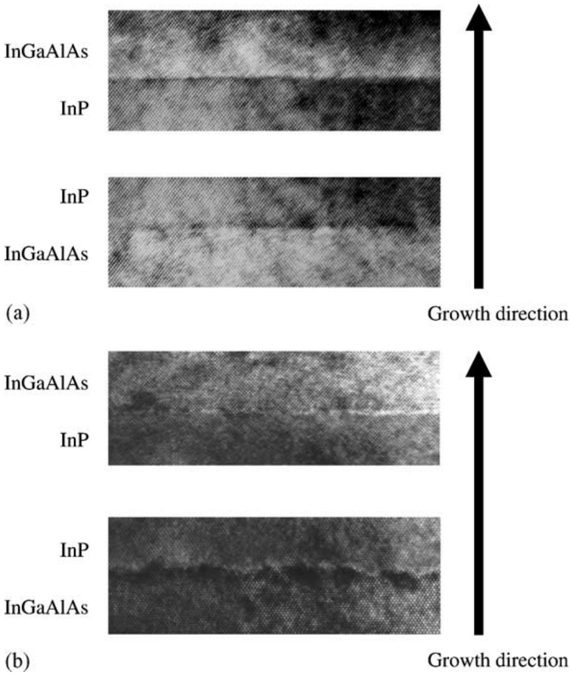


Fig. 1. The interface conditions of InP/InGaAlAs DBRs examined by TEM with different growth interruption time: (a) $t_p = 0.3$ min; (b) $t_p = 0$ min.

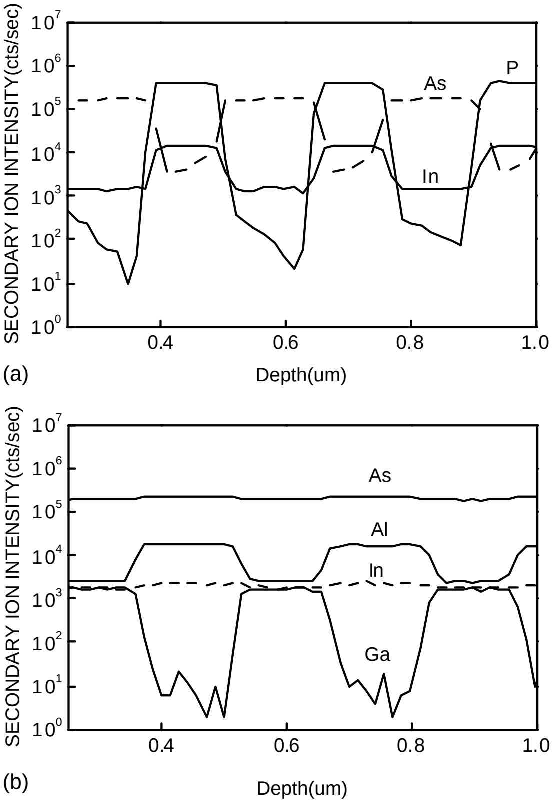
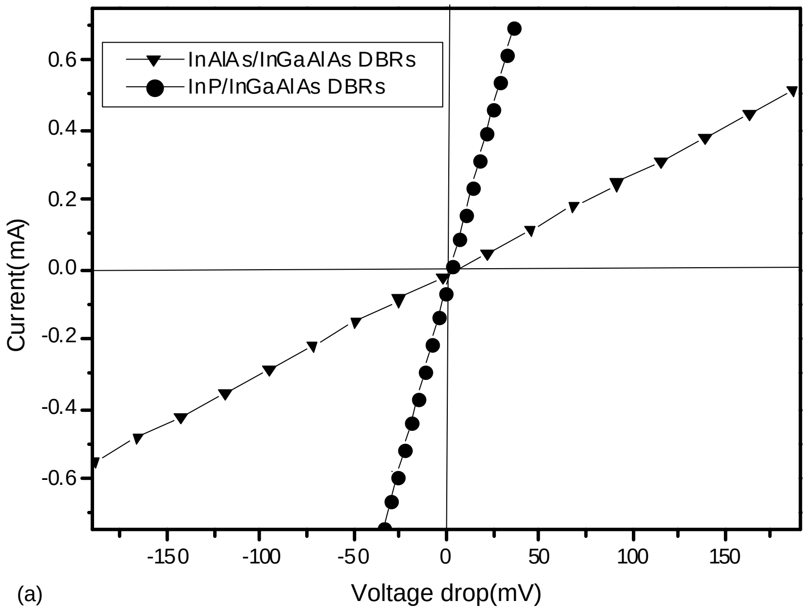


Fig. 2. The SIMS results of: (a) InP/InGaAlAs DBRs; (b) InAlAs/InGaAlAs DBRs.

growth interruption time. The growth sequence is indicated as the arrow direction. Fig. 1(a) is for the optimized growth condition with interruption time of 0.3 min. As can be seen, the interfaces between the InP and InGaAlAs are clear and abrupt. Fig. 1(b) shows the interfaces when the interruption time was 0 min. Some dark clusters can be seen at the interface between the InGaAlAs and InP. However, the interface between InP and InGaAlAs did not contain these dark clusters. We attribute the dark clusters to the As carry-over effect when grown under the non-optimized growth condition. The lattice-mismatched InAsP formed at the interface and became defects. These defects elongated upward to form the pits while the growth continues and reduce the reflectivity of the DBRs. On the contrary, there is no need to consider the interface switching problems to grow the InAlAs/InGaAlAs DBRs. The abrupt interface can be obtained without the interruption time between consecutive layers.

The SIMS results of InP/InGaAlAs and InAlAs/InGaAlAs DBRs are shown in Fig. 2 (a) and (b), respectively. Fig. 2(a) clearly indicates very low As carry-over for growth of InP/InGaAlAs DBRs under the optimized growth condition. Fig. 2(b) also shows the abrupt InAlAs and InGaAlAs transition at the interface for reference. Fig. 3(a) shows the *I–V* curves of the InP/InGaAlAs and InAlAs/InGaAlAs DBRs with round mesas of 50 μm in diameter. The resistance per DBR pair is calculated to be 1.2×10^{-5} and $2.2 \times 10^{-5}\ \Omega\,\mathrm{cm}^2$ for InP/InGaAlAs and InAlAs/InGaAlAs DBRs, respectively. The lower value of the resistance of the InP/InGaAlAs is due to the smaller conduction band discontinuity ($\Delta E_c = 0.15$ for InP/InGaAlAs; $\Delta E_c = 0.47$ for InAlAs/InGaAlAs [9]) between two layers. Fig. 3(b) shows the simulated equilibrium band diagrams of the InP/InGaAlAs and InAlAs/InGaAlAs DBRs for the n-type concentration of $1 \times 10^{18}\ \mathrm{cm}^{-3}$. The results suggest that the voltage drop is mainly located at the interface to overcome the potential barrier. Further reduction in the resistance value can be achieved by modulation doping of the interfaces of the DBR structure to lower the potential barriers.

Two DBR structures with 35 pairs of InP/$In_{0.53}Ga_{0.39}Al_{0.08}As$ and 35 pairs of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.39}Al_{0.08}As$



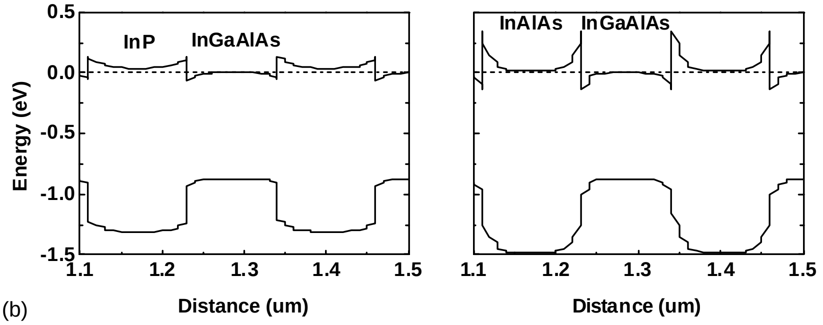


Fig. 3. (a) The *I–V* curves of InP/InGaAlAs and InAlAs/InGaAlAs DBRs with round mesas of 50 μm in diameter. (b) Simulation of the equilibrium band diagrams of the InP/InGaAlAs and InAlAs/InGaAlAs DBRs when the n-type concentration was chosen to be $1 \times 10^{18}\ \mathrm{cm}^{-3}$. The dashed line is the Fermi level.

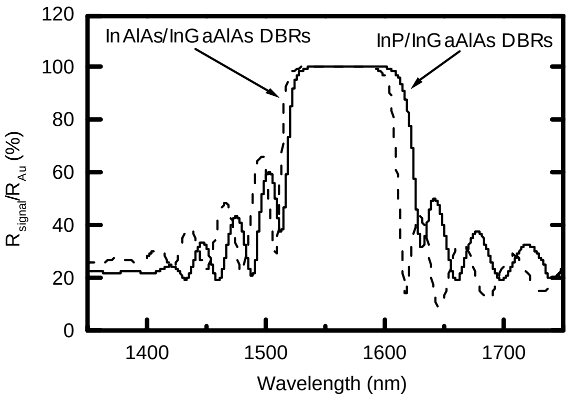


Fig. 4. The reflectivity curves of 35 pairs of InP/InGaAlAs and InAlAs/InGaAlAs DBRs measured by the spectrometer.

were then grown for comparisons using the same interruption time t_p of 0.3 min for growth of InP/$In_{0.53}Ga_{0.39}Al_{0.08}As$ DBRs. Fig. 4 shows the reflectivity curves of these two samples measured by the spectrometer. The measured reflectivity of samples was normalized to the reflectivity of the Au film. The maximum reflectivity of both DBRs exceeds 99% at center wavelength at 1.57 and 1.56 μm with the stopband width of 110 nm and 100 nm for the InP/InGaAlAs and InAlAs/InGaAlAs DBRs, respectively. The results of the reflectivity and the stopband width for the InP/InGaAlAs and InAlAs/InGaAlAs DBRs grown by MOCVD are comparable with the previous reports [9,12]. The InP/InGaAlAs DBR has wider stopband because of its larger refractive index contrast ($\Delta n = 0.34$ for InP/InGaAlAs; $\Delta n = 0.3$ for InAlAs/InGaAlAs [9]). However, the maximum reflectivity of the InP/InGaAlAs DBRs is susceptible to variation of the growth conditions.

4. Summary

In summary, we have grown the InP/InGaAlAs and the InAlAs/InGaAlAs DBRs with excellent electrical and optical properties using MOCVD and the growth interruption technique. The DBRs show low resistance with an estimated resistance per DBR pair of 1.2×10^{-5} and $2.2 \times 10^{-5}\,\Omega\,\text{cm}^2$ for InP/InGaAlAs and InAlAs/InGaAlAs DBRs, respectively. The maximum reflectivity of both DBRs exceeds 99% with a stopband width of 110 nm for InP/InGaAlAs DBR and 100 nm InAlAs/InGaAlAs DBR. Although the InP/InGaAlAs DBRs have better optical and electrical properties, the InAlAs/InGaAlAs DBRs has much lower growth complexity. Both DBR structures should be applicable for fabrication of long wavelength VCSELs in 1.5–1.6 μm range.

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References

[1] D.I. Babic, J. Piprek, K. Streubel, R.P. Mirin, N.M. Margalit, D.E. Mars, J.E. Bowers, E.L. Hu, IEEE J. Quantum Electron. 33 (8) (1997) 1369–1383.
[2] Y. Ohiso, C. Amano, Y. Itoh, H. Takenouchi, T. Kurokawa, IEEE J. Quantum Electron. 34 (10) (1998) 1904–1913.
[3] S. Sato, N. Nishiyama, T. Miyamoto, T. Takahashi, N. Jikutani, M. Arai, A. Matsutani, F. Koyama, K. Iga, Electron. Lett. 36 (24) (2000) 2018–2019.
[4] G. Steinle, F. Mederer, M. Kicherer, R. Michalzik, G. Kristen, A.Y. Egorov, H. Riechert, H.D. Wolf, K.J. Ebeling, Electron. Lett. 37 (10) (2001) 632–634.
[5] E. Hall, H. Kroemer, L.A. Coldren, Electron. Lett. 35 (5) (1999) 425–427.
[6] E. Hall, S. Nakagawa, G. Almuneau, J.K. Kim, L.A. Coldren, Electron. Lett. 36 (17) (2000) 1465–1467.
[7] I. Sagnes, G. Le Roux, C. Meriadec, A. Mereuta, G. Saint-Girons, M. Bensoussan, Electron. Lett. 37 (37) (2001) 500–501.
[8] M. Linnik, A. Christou, IEEE Trans. Electron. Devices 48 (10) (2001) 2228–2237.
[9] M.H.M. Reddy, T. Asano, R. Koda, D.A. Buell, L.A. Coldren, Electron. Lett. 38 (20) (2002) 1181–1182.
[10] J.P. Debray, I. Sagnes, G. Le Roux, P. Legay, M. Quillec, C. Kazmierski, R. Madani, J.F. Palmier, IEEE Photonics Technol. Lett. 11 (7) (1999) 770–772.
[11] T.C. Lu, J.Y. Tsai, J.T. Chu, Y.S. Chang, S.C. Wang, J. Cryst. Growth 250 (2003) 305–312.
[12] J.-H. Baek, I.H. Choi, B. Lee, W.S. Han, H.K. Cho, Appl. Phys. Lett. 75 (11) (1999) 1500–1502.