Semiconductor optical amplifier optical gate with graded strained bulk-like active structure

Ruiying Zhang
Jie Dong
National Research Center for Optoelectronic Technology
Institute of Semiconductors
Chinese Academy of Sciences
P.O. Box 912
Beijing 100083
China
E-mail: ryzhang@red.semi.ac.cn

Zhiwei Feng
Changchun Institute of Optics and Fine Mechanics
Changchun 130022
China

Fan Zhou
Huiliang Tian
Huiyun Shu
Lingjuan Zhao
Jing Bian
Wei Wang
National Research Center for Optoelectronic Technology
Institute of Semiconductors
Chinese Academy of Sciences
P.O. Box 912
Beijing 100083
China

Abstract. A novel semiconductor optical amplifier (SOA) optical gate with a graded strained bulk-like active structure is proposed. A fiber-to-fiber gain of 10 dB when the coupling loss reaches 7 dB/factet and a polarization insensitivity of less than 0.9 dB for multiwavelength and different power input signals over the whole operation current are obtained. Moreover, for our SOA optical gate, a no-loss current of 50 to 70 mA and an extinction ratio of more than 50 dB are realized when the injection current is more than no-loss current, and the maximum extinction ratio reaches 71 dB, which is critical for crosstalk suppression. [DOI: 10.1117/1.1539053]

Subject terms: graded strained bulk-like active structure; semiconductor optical amplifier; optical gate.

Paper 020071 received Mar. 6, 2002; revised manuscript received Jul. 3, 2002; accepted for publication Sep. 11, 2002.

1 Introduction

In the near future, photonic wavelength-division multiplexing (WDM) systems will require a number of optical gate elements for both routing and buffering operations.[1] Compared with other components as optical gates, a semiconductor optical amplifier (SOA) is a promising candidate as an on and off gate array to fabricate switch matrices for optical path cross connection, add-drop multiplexes, and asynchronous transfer mode cell switching due to their capacity of providing no-loss operation, fiber-to-fiber gain, and a large optical extinction ratio over wide wavelength range.[2]

In developing SOA gates into functional and efficient optical components, one serious problem is the wide bandwidth polarization insensitivity over a large operation current. For the realization of such a characteristic, multiple-quantum-well (MQW) active structures are given up because different gain variations for TE and TM modes can be induced when signal wavelength or injection current changes.[3] A quasi-square unstrained bulk active structure is an ideal selection for an SOA optical gate. However, narrow stripe width (<0.5 μm) is difficult to fabricate by either growth technology or etching technology.[4,5] A single tensile bulk active structure overcomes the narrow stripe width limitation, and good polarization insensitivity has been obtained. In addition, it is possible to obtain high fiber-to-fiber gain by using the optimized whole device design.[6] However, it is difficult to obtain high crystal quality when the single tensile bulk active layer is more than 100 nm, because it is inevitable for such semicoherent growth to induce dislocation although there is no lattice relaxation evidence. Using a graded-strain bulk-like (GSBL) active structure to fabricate an SOA gate was recently proposed.[7] Such an active structure is an ideal selection because it can overcome both the narrow-stripe width limitation due to the tensile strain layer introduction and the dislocation appearance due to thinner tensile strain layer and distribution separately. In addition, compared with a single tensile bulk active region, a GSBL structure has a wider and flatter gain spectrum due to the multiple recombination wavelengths in this structure, which favors obtaining a wider polarization-insensitive gain bandwidth and multiwavelength signal amplification. The polarization insensitivity characteristics were analyzed from the point of theory.[7,8] In this paper, we present their characteristics as an optical gate, which shows that such an SOA is an efficient and functional device in this context.

2 Device Design and Fabrication

A GSBL active structure is based on the facts that the tensile strain can enhance the TM mode material gain and

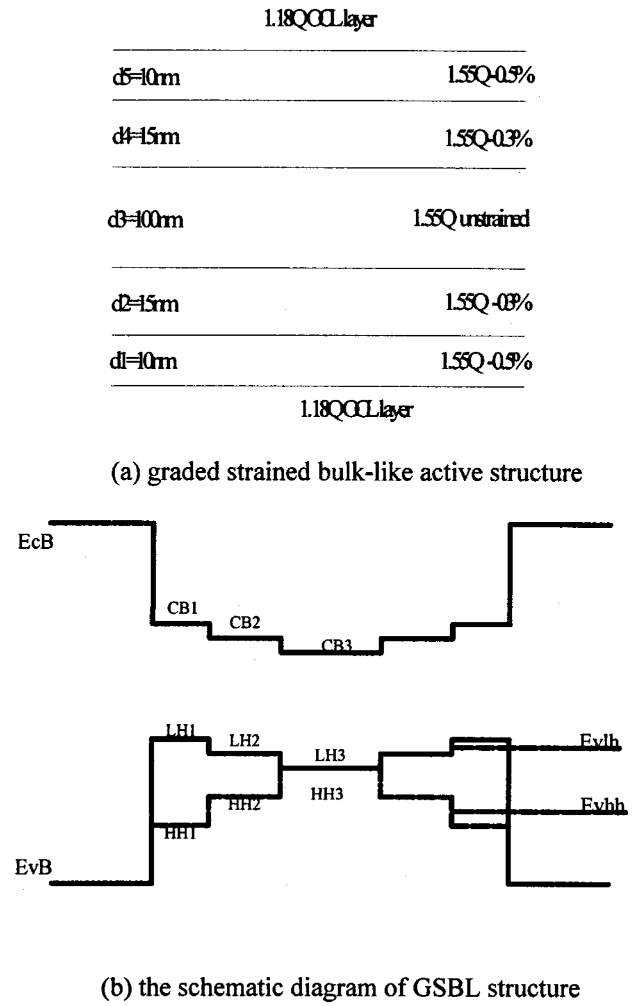


Fig. 1 (a) GSBL active structure and (b) its schematic diagram.

relax the limitation of narrow stripe width, that a thin strain layer distribution can enhance the active layer quality, and that the whole active region including the different materials can reduce multirecombination wavelengths and further expand the gain spectrum bandwidth. The active layer structure is schematically shown in Fig. 1(a). The active layers are sandwiched between upper (150-nm-thick) and lower (150-nm-thick) InGaAsP optical confinement layers with a bandgap wavelength of 1.18 μm. The layers with different strains and different thicknesses are distributed, respectively, in terms of the whole structure polarization insensitivity and the flat gain spectrum bandwidth. Note that the different strains refers to both type and amount of the strain. An energy band diagram of this structure is shown in Fig. 1(b). The center of this active structure is lattice-matched bulk layer, which has a degenerated valence band and provides the same TE and TM mode material gain. As the tensile stress increases, both the light-hole band edge and conduction band edge shape the same shallow trapezium, whereas the heavy-hole band edge forms a contrary trapezium. Such an energy band structure results in both the transition wavelength between electrons and light holes being unchanged, and that between electrons and heavy holes becoming shorter and shorter in the whole active structure. Device mode gain is the weighted sum of material gain in each layer, and the weighting factor is the corresponding optical confinement factor. As a result, the wide-bandwidth TE mode gain spectrum will be obtained due to multiwavelength recombination between electrons and heavy holes in tensile strain layers, however, the wide-bandwidth TM mode gain will be obtained because the smaller effective masses for electron and light holes lead to the band-filling effect significantly with the injection current. Meanwhile, it is possible to achieve a wide polarization-insensitive bandwidth due to the large optical confinement factor in unstrained material. Detailed theoretical analysis has been published in Ref. 8.

Such an SOA is fabricated using three-step metal-organic vapor phase epitaxy (MOVPE) process. For the first growth, the 0.5-μm *n*-doped InP buffer layer, the 150-nm-thick 1.18-μm-bandgap InGaAsP quaternary lower optical confinement layer, the 150-nm-thick GSBL active structure just as shown in Fig. 1(a), the 150-nm-thick 1.18-μm-bandgap InGaAsP quaternary upper optical confinement layer, and the 100-nm-thick *p*-doped InP cladding layer are grown by conventional MOVPE technology separately. Then, standard contact photolithography combined with chemical etching through the patterned photoresist is used for the 1.5-μm-wide active waveguide definition along the direction tilted 7 deg with respect to [1,1,0] crystalline direction. For the second growth, *p*-*n*-*p* current-blocking layers are grown by low pressure MOVPE (LP-

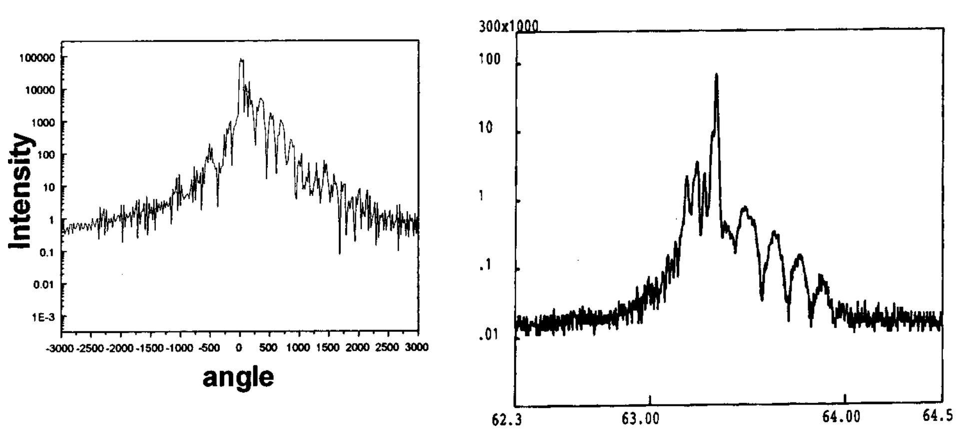


Fig. 2 X-ray simulation (left) and measurement (right) results for the GSBL structure.

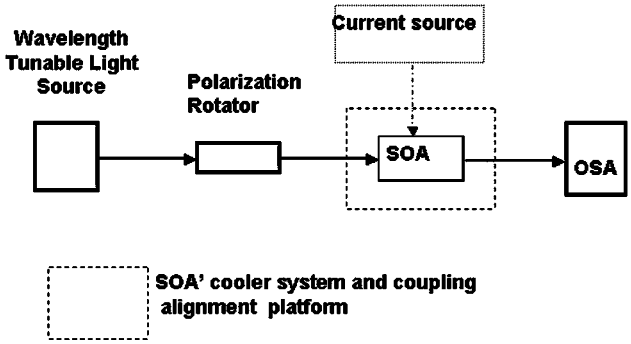


Fig. 3 SOA optical gate static measurement system.

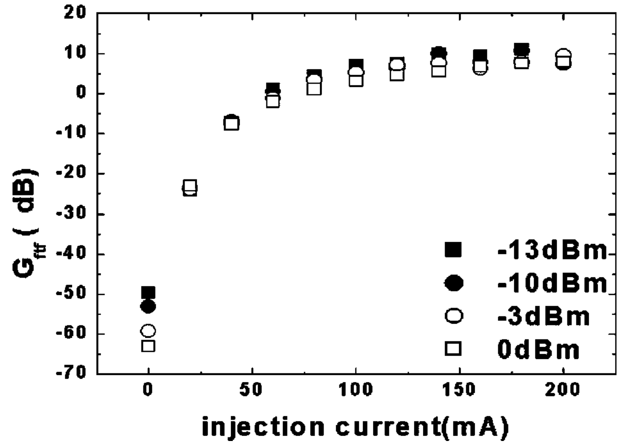


Fig. 5 Fiber-to-fiber gain dependence of operation current at different input signal light powers for the SOA gate.

MOVPE). The nearly 3-μm-thick *p*-InP layer and the 100-nm-thick P^+-InGaAs contact layer are grown in turn by the third LP-MOVPE technology. After the electrodes are finished, antireflection (AR) coating proceed with $SiO_x/SiON_x$ to further reduce facet reflectivity. Finally, 600-μm-long devices are cleaved along the $[1,-1,0]$ direction.

To verify the GSBL active structure crystal quality, x-ray simulation and measurement results are shown in Fig. 2 respectively. The similarity of both results and no relaxation evidence prove that such a GSBL structure has good crystal quality, which favors the SOA obtaining good characteristics.

To measure such SOA optical gate characteristics, we adopt the measurement system shown in Fig. 3. Coupling loss between the device and AR-lens single-mode fiber reaches 7 dB/facet. The polarization controller may ensure that the exact polarization dependence loss has been measured. An optical spectrum analyzer was used to protect the signal characteristic measurements from ASE noise.

3 Device Characteristics

The amplified spontaneous emission (ASE) spectrum of such an SOA at an injection current of 120 mA is shown in Fig. 4. The 3-dB bandwidth of about 43 nm and a ripple of about 0.5 dB were obtained at an injection current of 120 mA. Optimizing the AR coating design will expand the 3-dB bandwidth for such a device. The blue shift of the ASE spectrum results from the band-filling effect at a large current bias. Thus, it is indispensable for fabricating *C* band SOA to select longer wavelength InGaAsP material. Figure 5 shows the fiber-to-fiber gain versus the driving current when the optical input signal power is 0, -3, -10, and -13 dBm with a wavelength of 1520 nm. For all kinds of optical input signals, no-loss operation current is between 50 and 75 mA, and the maximum fiber-to-fiber gain reaches 10-dB at driving current of nearly 150 mA, which is high enough to act as an optical gate. Figure 6 shows that the gain flatness is about 2 dB for a signal wavelength of 1510 to 1530 nm at different operation currents. And about 10 dB fiber-to-fiber gain at a driving current of 160 mA was obtained for different wavelength input signals. The preceding results indicate that our SOA optical gate is suitable to operation for various wavelengths and various power input optical signal gatings. In addition, smaller gain for our device is related with larger coupling loss and higher power input signal.

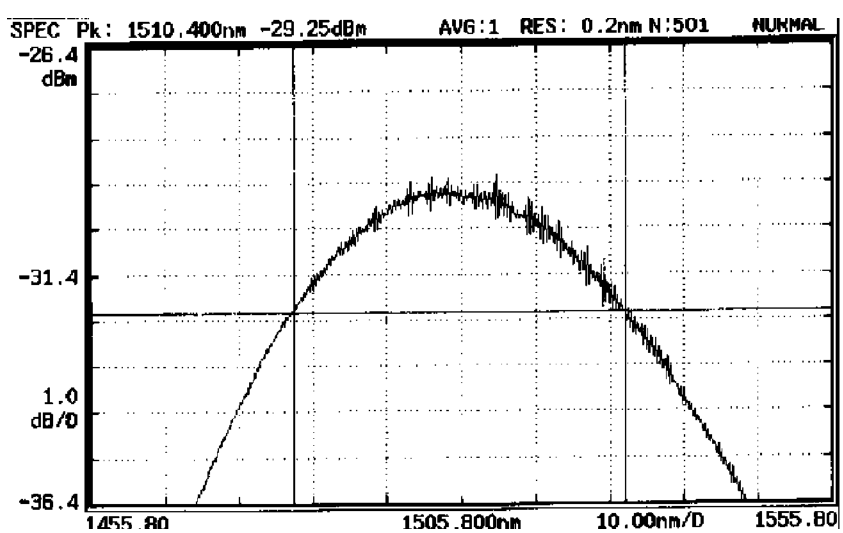


Fig. 4 ASE spectrum of the SOA at injection current of 120 mA.

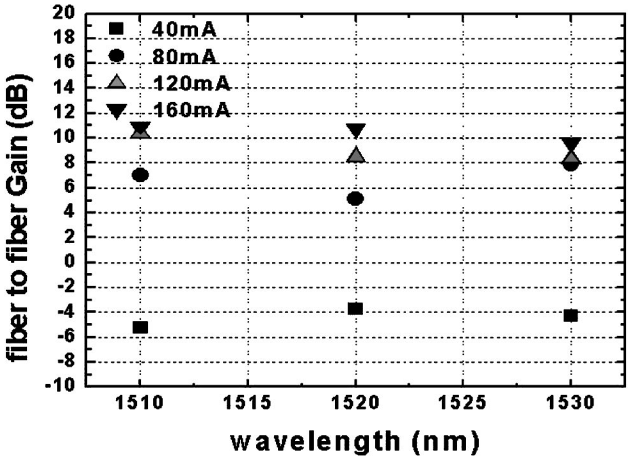


Fig. 6 Fiber-to-fiber gain versus signal light wavelength at different driving currents for the SOA gate.

Figure 7 shows the polarization dependence loss (PDL) variation with the injection current for different input signal wavelengths at an input signal power of −13 dBm. We can observe that for all kinds of optical input signals, the PDL always fluctuates between 0 and 0.9 dB with the operation current, which indicates that such SOA can realize nearly polarization-insensitive gating for a wide optical input signal wavelength range.

A large extinction ratio is another advantage of an SOA optical gate. Figure 8 shows the extinction ratio versus driving current for different power input signals. And the input signal wavelength is 1520 nm. Figure 8 indicates that the higher the input signal power, the larger the extinction ratio. And the maximum extinction ratio of 71 dB was achieved for an input signal power of 0 dBm at injection current of 200 mA. More than 50 dB of extinction ratio was achieved when the injection current was more than 60 mA for every input signal, which is compared with NEC's result.[9] And switching time will be measured in the near future.

4 Conclusions

A novel semiconductor optical amplifier gate with graded strained bulk-like active region has been designed and fabricated. The fabrication process is simple, compatible with a conventional buried heterostructure laser diode (BH LD) process. Measurements indicate that this device has very low polarization dependence (<0.9 dB), high extinction ratio (>50 dB), a maximum fiber-to-fiber gain of 10 dB, and lossless operation currents of 50 to 75 mA for an input signal with different wavelength and power. Such results are enough to satisfy the optical gating demand. Further optimization of the active structure and enhancement of the coupling efficiency will be helpful for the device characteristics. The switching time will be measured in the near future.

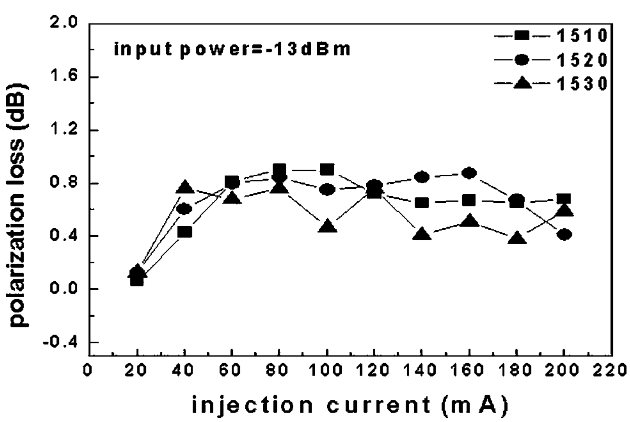


Fig. 7 Polarization characteristics versus driving current for the SOA gate.

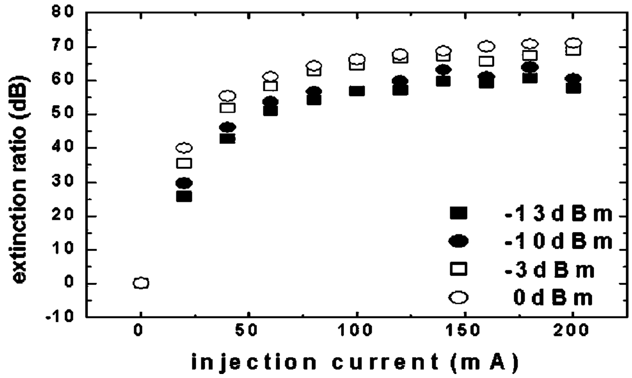


Fig. 8 Extinction ratio characteristics versus driving current at different input signal light powers for the SOA gate.

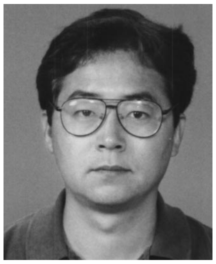
Acknowledgments

This work is supported by National 973 project (Grant No. G20000683-1) and National Nature Science Foundation of China (Grant No. 90101023).

References

1. K. Sasayama, K. Habara, Z. W. De, and K. Yukiatsu, "Photonic ATM switch using frequency-routing-type time division interconnection network," *Electron. Lett.* **29**(20), 1778–1780 (1993).
2. T. Ito, N. Yoshimoto, K. Magari, Kishi, and Y. Kondo, "Extremely low power consumption semiconductor optical amplifier gate for WDM applications" *Electron. Lett.* **33**(21), 1791–1792 (1997).
3. S. Seki, T. Yamanaka, W. Lui, Y. Yoshikuni, and K. Yokoyama, "Theory analysis of pure effects of strain and quantum-well lasers," *IEEE J. Quantum Electron.* **30**, 500–510 (1994).
4. S. Kitamura, H. Hatakeyama, K. Hamamoto, T. Sasaki, K. Komatsu, and M. Yamaguchi, "Spot-size converter Integrated semiconductor optical amplifiers for optical gate application," *IEEE J. Quantum Electron.* **35**, 1067–1073 (1999).
5. K. Kato and Y. Tohmori, "PLC hybrid integration technology and its application to photonic components," *IEEE J. Quantum Electron.* **6**, 4–12 (2000).
6. M. Bachmann, P. Doussiere, J. Y. Emery, R. N. Go, F. Pommereau, L. Goldstein, G. Soulage, and A. Jourdan, "Polarization-insensitive clamped-gian SOA with integrated spot-size covertor and DBR gratings for WDM applications at 1.55 μm wavelength," *Electron. Lett.* **32**, 2076–2077 (1996).
7. R. Y. Zhang, J. Dong, F. Zhou, H. L. Zhu, H. Y. Shu, J. Bian, L. F. Wang, H. L. Tian, and W. Wang, "A novel polarization-insensitive semiconductor optical amplifier structure with large 3-dB bandwidth," in *Optoelectronics, Materials, and Devices for Communications*, T. P. Lee and Q. Wang, Eds., *Proc. SPIE* **4580**, 116–123 (2001).
8. R. Zhang, J. Dong, J. Zhang, Z. Feng, and W. Wang, "The theory analysis for semiconductor optical amplifier with large 3dB bandwidth," *Chin. J. Semicond.* **23**(8), (2002).
9. S. Kitamura, H. Hatakeyama, T. Tamanuki, T. S.-K. Komatsu, and M. Yamaguchi, "Angled-facet S-bend semiconductor optical amplifiers for high-gain and large-extinction ratio," *IEEE Photonics Technol. Lett.* **11**(7), 788–790 (1999).

Ruiying Zhang received her BS degree in physics from Inner Mongolia University for Nationalities, her MS degree in theoretical physics from He Nan Normal University, and her PhD degree in microelectronics and solid state electronics from the Institute of Semiconductors, Chinese Academy of Sciences, in 2002. She has been engaged in research on the fabrication of a semiconductor optical amplifier since 2000.



Jie Dong received his MS degree in electronic engineering from Tsinghua University, China, in 1988, and his PhD degree in electrical engineering from Tokyo Institute of Technology, Japan, in 1993. In 1993, he joined Tsukuba Laboratories, Nippon Sanso Co., Japan, where he worked on laser design, MOCVD growth, and laser process development of InGaAsP/InP material long-wavelength DFB lasers. He also worked on MOCVD growth of AlGaAs/GaAs LED on Si. In 2000, as a professor, he joined the Institute of Semiconductors, Chinese Academy of Sciences, where he majored in the research of monolithic integrated devices such as SOA, EA modulators, and EML. In 2001, he joined Archcom Technology (Shenzhen) Inc., China. Now he is engaging in mass production of 1.3 μm and 1.5 μm lasers. Dr. Dong authored and/or co-authored more than 60 scientific papers in both journals and conferences. He is a member of IEEE/LEOS.

Wei Wang graduated from the Physics Faculty, Peking University, in 1960 and then joined the Institute of Semiconductors, Chinese Academy of Sciences, where he was with the Silicon and GaAs Crystal Material Division from 1960 to 1970, and since 1971 with the Semiconductor Optoelectronic Division, engaged in research on GaAs/GaAlAs single-heterostructure/double-heterostructure (SH/DH) laser diodes (LDs), GaAs/GaAlAs high-radiance LEDs, 1.3- and 1.5-μm InGaAsP/InP Fabry-Pérot LDs, and distributed Bragg reflector/distributed feedback (DFB/DBR) LDs, 1.3- and 1.5-μm strained layer multiple quantum well DFB lasers, high-speed polarization insensitive electroabsorption modulators, polarization-insensitive semiconductor optical amplifiers, and EMLs. Mr. Wang has been a member of Chinese Academy of Sciences since 1997 and is a member of Optical Society of America.

Biographies and photographs of other authors not available.