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Optimization for Top DBR's Reflectivity in RCE Photodectector*

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Abstract: The monolithic integration of vertical-cavity surface-emitting lasers (VCSEL) with photodetectors is very important in the application of free-space optical interconnects. Theoretical and experimental results on the resonant-cavity-enhanced (RCE) photodetector with VCSEL Structure are presented. The compatible requirement in input mirror reflectivity between the VCSEL and the RCE detector is achieved by precisely etching the top mirror. In this way, the RCE detector with relatively high quantum efficiency and necessary optical bandwidth has been obtained.

Key words: vertical-cavity surface-emitting laser; resonant-cavity-enhanced photodetector; distributed Bragg reflector; free-space optical interconnects

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1 Introduction

Considerable interest has been found in the free-space optical interconnects (FSOI's) for their potential in relieving the electrical interconnects of bottle-necks. The channel density of FSOI's is inherently two-dimensional (2-D), which is suitable for the board-to-board and chip-to-chip interconnects.

Vertical-cavity surface-emitting lasers (VCSEL's) are promising light sources for optical interconnects owing to their advantages, such as low threshold current, single mode operation, low beam divergence, high-modulated speed, and two-dimensional array fabrication. To fully utilize the 2-D nature of the optical interconnects, it is desirable that we should have the integrated arrays of VCSEL's and photo-detectors. Flip-chip bonding is one of the methods of packaging 2-D array of VCSEL's with detectors, which needs very precise alignment[1]. Another integration technique is using the patterned re-growth, i.e., one device structure has been grown with epilayers in this field and selectively removed before the other device structure was grown. This method reduces the device yield, and increases the complexity of the fabrication at the same time, thus it leads to a substantial increase of the cost. Another integration technique is to use the same technology for both VCSEL and detector, i.e., to use a resonant-cavity-enhanced (RCE) photodetector[2]. RCE photodetector has the properties such as wavelength-selectivity, high quantum efficiency, and high-speed response[3,4]. VCSEL and RCE photodetector are both resonant-cavity-enhanced photonic devices, with the fundamental structure of multiple quantum wells sandwiched between two high-reflectivity DBR (distributed Bragg reflector) mirrors, though they have different requirements for the input/output mir-

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ror. They can be fabricated in the same wafer with almost the same technology to realize the relatively simple monolithic integration.

Using the method of chemical etching, we precisely alter the reflectivity of a resonant cavity to study how the detector's quantum efficiency and the optical bandwidth vary with the top mirror's reflectivity. And finally a RCE photodetector with comparatively high quantum efficiency and a reasonable optical bandwidth is obtained.

2 Analysis

VCSEL and RCE photodetector are both resonant-cavity-enhanced photonic devices whose active structure (lasing region or absorption region) is placed inside a DBR resonant cavity. The detailed structure is illustrated in Fig. 2. In such a structure, though most of the device functions are same as before, they are effected by the cavity: wavelength selectivity and large enhancement in the resonant optical field.

The quantum efficiency of RCE photodetector can be written as[5]

$$\eta = (1-R_{in})(1+R_{back}e^{-\Gamma_{enh}\alpha d})(1-e^{-\Gamma_{enh}\alpha d})/ (1-2\sqrt{R_{in}R_{back}}e^{-\Gamma_{enh}\alpha d}\cos(2\beta L+\Psi_1+\Psi_2) + R_{in}R_{back}e^{-2\Gamma_{enh}\alpha d})$$

where the propagation constant $\beta = 2\pi n/\lambda_0$, λ_0 is the vacuum wavelength, n is the refractive index; L is the cavity length, R_{in} and R_{back} are the input (top) and back (bottom) mirror reflectivity, respectively, α is the absorption coefficient and d is the total thickness of the absorbing material. Γ_{enh} is the standing wave enhancement factor, Ψ_1 and Ψ_2 are the phase shifts due to the light penetrating the input and back mirrors separately.

Since β is of wavelength dependence, η is a periodic function of the inverse wavelength. Contrast to the conventional detector, even though with a comparatively thin absorption layer, devices are of high quantum efficiency owing to the resonant cavity, and of high-speed response as well.

η is enhanced periodically with the resonant wavelengths when $2\beta L+\Psi_1+\Psi_2 = 2m\pi (m=1, 2, 3, \cdots)$. The peak quantum efficiency η_p and the FWHM optical bandwidth $\Delta\lambda_{1/2}$ are given by[5]

$$\eta_p = \frac{(1-R_{in})(1+R_{back}e^{-\Gamma_{enh}\alpha d})(1-e^{-\Gamma_{enh}\alpha d})}{(1-\sqrt{R_{in}R_{back}}e^{-\Gamma_{enh}\alpha d})^2}$$

$$\text{FWHM} = \Delta\lambda_{1/2} = \frac{\lambda\lambda_0}{2\pi L_{eff}} \times \frac{(1-\sqrt{R_{in}R_{back}}e^{-\Gamma_{enh}\alpha d})}{2\pi L_{eff}(R_{in}R_{back})^{1/4}e^{-\Gamma_{enh}\alpha d/2}}$$

where λ is the resonant wavelength of the detector, and L_{eff} is the effective cavity length, which is the multiple of the resonant wavelength.

Figure 1 shows the relationship between η_p, $\Delta\lambda_{1/2}$ and R_{in}, assuming that $\alpha = 6000\text{cm}^{-1}$, $L_{eff} = 3.5\lambda$, $\Gamma_{enh} \approx 1.83$, $d = 24\text{nm}$ (the absorption region is composed of three 8nm $In_{0.2}Ga_{0.8}As/GaAs$ QW's), and $\lambda_0 = 980\text{nm}$. The four curves represent η_p and $\Delta\lambda_{1/2}$ versus R_{in} at different back mirror reflectivity. From this figure, it can be seen that, when R_{in} increases, $\Delta\lambda_{1/2}$ will increase accordingly, while η_p will increase first and then decrease. When $R_{in} = R_{back}e^{-2\Gamma_{enh}\alpha d}$, the maximized η_p is obtained.

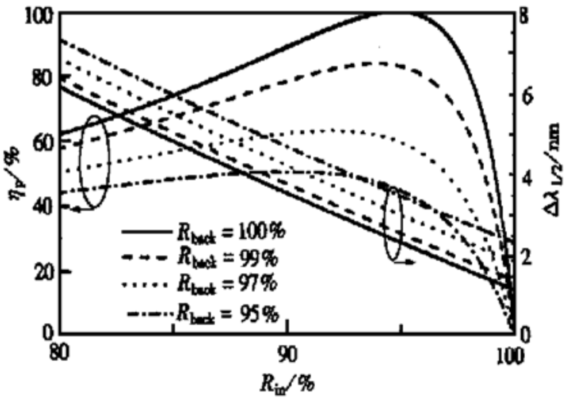

FIG. 1 Quantum Efficiency and Optical Bandwidth Versus Input Mirror Reflectivity for Resonant-Cavity Detector

For a FSOI, the bandwidth is rather wide, such as ranging between 5—6nm. A wide optical bandwidth is required to tolerate the variations in wavelength over a wafer and from one wafer to the other, as well as the differences in operating temperatures between different arrays. It can be seen in Fig. 1 that a VCSEL (with R_{in} larger than 99%)

acting as a detector, devices with low quantum efficiency and narrow optical bandwidth can be yielded. By reducing the R_{in} to about 95%, the detector has the maximum quantum efficiency but a fairly narrow optical bandwidth. To obtain a wider optical bandwidth, the R_{in} should be reduced further, thus the quantum efficiency is traded for the optical bandwidth. With a proper input mirror reflectivity selected, the detector with both the reasonably large optical bandwidth and the adequate absorption can be obtained. In this paper, we have presented a wet chemical etching method to alter the input mirror reflectivity of device, and measured the quantum efficiency spectrum that varies with R_{in}.

3 Results and Discussion

The device structure was grown by MOCVD on an N^+-doped GaAs substrate. As shown in Fig. 2, the epitaxial layers mainly consist of three parts. The bottom mirrors are 32 periods of n-doped $GaAs/Al_{0.9}Ga_{0.1}As$ DBR; the middle parts consisted of three undoped $In_{0.2}Ga_{0.8}As/GaAs$ quantum wells, which are cladded by $Al_{0.3}Ga_{0.7}As$ confined layers; and the top mirrors are 22 periods of P-doped $GaAs/Al_{0.9}Ga_{0.1}As$ DBR. The first top layer is P^+-doped GaAs as a contact. With this structure, we can fabricate a vertical-cavity surface-emitting laser, with the lateral oxidation operating at wave band of 980nm, and the threshold current of several hundred of microampere.

	P^+	GaAs	$\lambda/4$
	P	$Al_{0.9}Ga_{0.1}As$	$\lambda/4$
21×	P	GaAs	$\lambda/4$
	P	$Al_{0.9}Ga_{0.1}As$	$\lambda/4$
	I	$Al_{0.3}Ga_{0.7}As$	
3×	I	GaAs	8nm
	I	$In_{0.2}Ga_{0.8}As$	10nm
	I	GaAs	8nm
	I	$Al_{0.3}Ga_{0.7}As$	
32×	N	GaAs	$\lambda/4$
	N	$Al_{0.9}Ga_{0.1}As$	$\lambda/4$
		GaAs Buffer	
	N^+	GaAs Substrate	

FIG. 2 Structure of VCSEL Wafer

Figure 3 is the measured reflectivity spectrum for the epitaxial wafer. The resonant wavelength has been designed to be 980nm originally. During the growth of the materials by MOCVD, the variation in wavelength will appear inevitably, owing to any deviation of structure thickness. The measured variation of the wafer is about 3nm/mm. The resonant wavelength we measured in this paper is 958.4nm, at the center of the high reflectivity band.

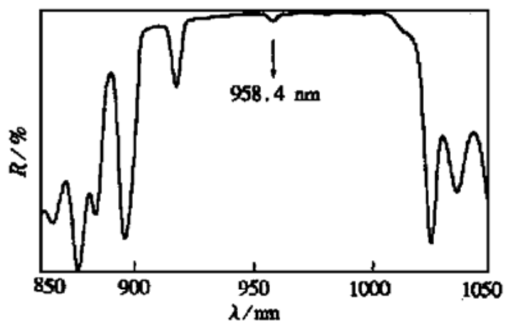

FIG. 3 Measured Reflectivity of Wafer

The RCE photodetectors using this VCSEL structure epitaxial wafer have been fabricated. The measured photocurrent spectra are shown in Fig. 4. The wavelength of the peak photocurrent is 958.2nm exactly.

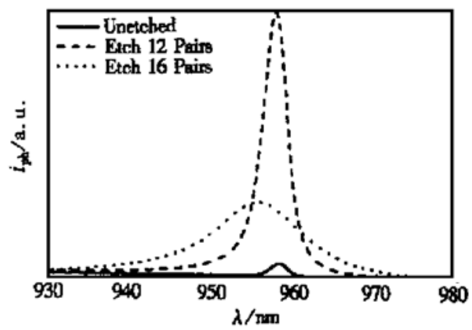

FIG. 4 Measured Photocurrent Spectra

The accurately controlled etching is used to alter the reflectivity of the input DBR progressively. Figure 4 is the photocurrent spectra we measured with different R_{in}, in which, the solid line denotes the device with a complete VCSEL epitaxial structure (unetched); the dash line denotes the one with 12 periods of top DBR etched off, while the dot line denotes the one with 16 periods of top DBR etched off. By lessening the top DBR's periods and decreasing the input mirror's reflectivity, the detector's quantum efficiency and the optical bandwidth would be changed obviously. As for the device with 12 periods being etched, the peak photocurrent increased 10 times as much as that of the unetched one, and the spectrum response broadened from 2nm to 3.6nm. As for the one with 16 periods etched, the spectrum bandwidth broadened continuously beyond 10nm but the peak photocurrent would decrease, and the spectrum would have a little blue shift for some unknown reason. Figure 5 are the measured curves of the peak value of photocurrent at the resonant wavelength, and its optical bandwidth versus the top mirror reflectivity as well, which is in agreement with the calculated results. Since the quality of the grown wafer is not so good as the designed one, and there exist some limitation from the experimental equipment and from the uniformity of the incident light, the measured optical bandwidth is larger than the calculated one, but the quantum efficiency is lower than the calculated one. With improved materials grown by MBE, the quantum efficiency can be greatly increased up to 80% with a narrower bandwidth, which will be published elsewhere.

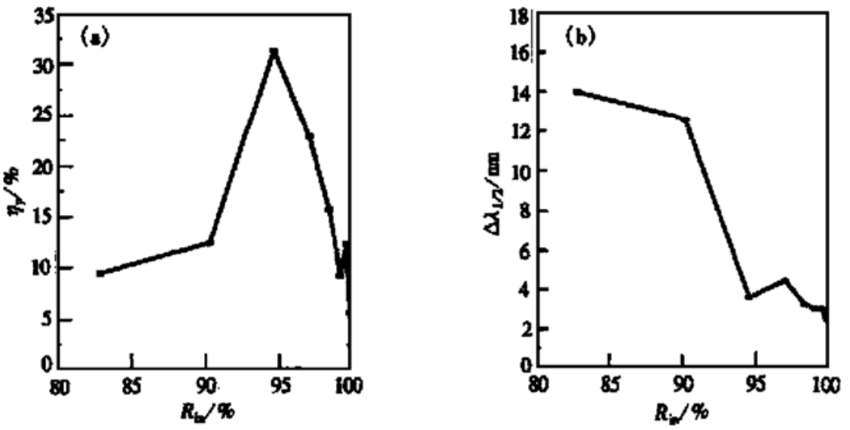

FIG.5 Measured Device Quantum Efficiency (a) and Spectrum Bandwidth (b) Versus Input Mirror Reflectivity

4 Conclusion

In this paper, we present the theoretical and experimental results of RCE photodetector with VCSEL structure. By properly etching the top DBR of device to alter the input mirror reflectivity, the RCE photodetector with both reasonably large optical bandwidth and adequate quantum efficiency can be realized. These results prove the potential of the monolithic integration of high performance VCSEL with RCE photodetector.

References

[1] CHEN Hong-da, LIANG Kun, ZENG Qing-ming *et al.*, Optoelectronic Smart Pixels Comprising Flip-Chip-Bonded GaAs/AlGaAs MQW Detectors and Modulators on Silicon CMOS Circuit, Chinese Journal of Semiconductors, 2000, **21**(8): 735—738.

[2] O. Sjolünd, D. A. Louderback and E. R. Hegblom, Monolithic Integration of Substrate Input/Output Resonant Photodetectors and Vertical-Cavity Lasers, IEEE J. Quantum Electron., 1999, **35**(7): 1015—1023.

[3] HUANG Yong-qing, LIU Kai and LI Jian-xin, Realization and Performance's Analysis of GaAs/AlGaAs Resonant-Cavity-Enhanced Photodetector, J. Optoelectronics Laser, 2000, **11** (1): 1—3.

[4] K. Kishino, M. S. Ünlü and J. I Chyi, Resonant Cavity Enhanced (RCE) Photodetectors, IEEE J. Quantum Electron., 1991, **27**(8): 2015—2034.

[5] M. S. Ünlü and S. Strite, Resonant Cavity Enhanced Photonic Device, J. Appl. Phys., 1995, **78**(2): 607—639.

RCE 光电探测器顶部 DBR 的优化*

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摘要: 对研制的 VCSEL 结构外延片制成的谐振腔增强型(简称 RCE) 光电探测器进行了物理分析和实验研究, 由于 VCSEL 与 RCE 光电探测器对谐振腔反射镜的反射率要求不同, 通过腐蚀 VCSEL 器件顶部 DBR, 改变顶镜反射率, 能够得到量子效率峰值和半宽优化兼容的 RCE 光电探测器, 实现 VCSEL 与 RCE 探测器的单片集成.

关键词: 垂直腔面发射激光器 (VCSEL); 谐振腔增强型 (RCE) 光电探测器; 分布式布拉格反射镜 (DBR); 自由空间光互连 (FSOI)

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