Lateral Oxidation in Vertical Cavity Surface Emitting Lasers

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Abstract: Lateral oxidation in vertical cavity surface emitting lasers (VCSELs) is described, and its characteristics are investigated. A linear growth law is found for stripe mesas. However, oxide growth (above 435 °C) follows a nonlinear law for the two geometry mesa structures which we employ in VCSEL. Theoretical analysis indicates that mesa structure geometry influences oxide growth rate at higher temperatures.

Key words: lateral oxidation; quantum well; vertical cavity surface emitting laser
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1 Introduction

The oxidation of AlAs (or AlGaAs with a high Al content) layers has been successfully employed in the fabrication of high-performance VCSELs[1,2]. Oxide layers have been used to form current apertures and index guiding. Oxide-confined VCSELs have exhibited the highest power conversion efficiency (> 50%)[3] and lowest threshold current[1]. But accurately controlling the oxidation process is difficult. Many researchers have investigated the characteristics of lateral oxidation[4~7]. However, there is considerable controversy over whether or not oxidation follows a linear or parabolic growth rate. Linear growth rates were reported for the lateral oxidation of $Al_{0.98}Ga_{0.02}As$[4]. Meanwhile, it has been reported for the lateral oxidation of AlAs that the oxide growth is initially linear over time and converts to parabolic growth as the oxide thickness increases[5]. In this paper we employ the partial oxidation of an $Al_{0.98}Ga_{0.02}As$ layer in the DBR mirror stack to form current apertures. We fabricate VCSELs and characterize their static properties using perforated ring (PR) instead of ring trench (RT) as lateral oxidation windows[8,9]. Here, the lateral oxidation of $Al_{0.98}Ga_{0.02}As$ in N_2/H_2O atmosphere is characterized with respect to oxidation temperature, N_2 carrier gas flow, and the geometry of the mesa structures.

2 Structure and experiment

The epitaxial structures used in this study were grown by molecular beam epitaxy (MBE) on n^+ GaAs substrates. The bottom Bragg reflector consisted of 34 n-type Si-doped $Al_{0.9}Ga_{0.1}As/GaAs$ pairs with quarter-wavelength-thick layers. The active region contained a GaAs-AlGaAs-based triple-quantum-well in a single wavelength cavity for 850nm emission. The top Bragg reflector consisted of 24 p-type C-doped $Al_{0.9}Ga_{0.1}As/GaAs$ pairs. An $Al_{0.98}Ga_{0.02}As$ layer used for the subsequent lateral oxidation was placed in the fourth quarter-wavelength layers above the active region.

Mesas with different geometries (stripes, ring trenches, and perforated rings) were etched by chemically assisted reactive ion beam etching (using Cl_2/BCl_3) down to the active layer, using silicon nitride as the etch mask. The exposed $Al_{0.98}Ga_{0.02}As$ layer was oxidized at different temperatures in N_2/H_2O atmosphere. Dry N_2 with a constant flow of 1.5L/min was used as carrier gas for H_2O vapor. Figure 1 shows the experimental setup.

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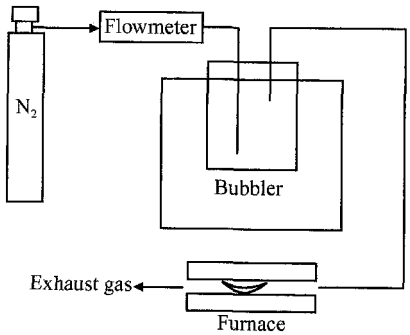

Fig. 1 Experimental setup for oxidation

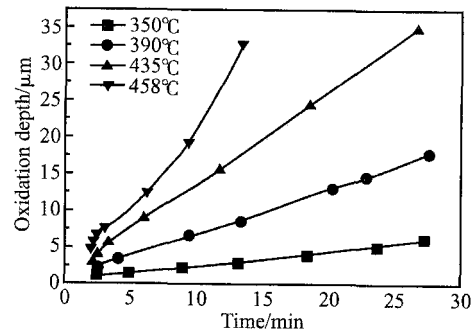

Fig. 4 Measured lateral oxidation depth versus time for mesa with PR at different temperatures

3 Experiment results and analysis

Figure 2 shows the lateral oxidation depth w versus oxidation time t at temperatures ranging from 350 to 460 ℃ for the stripe mesa. A linear behavior of the oxidation depth is observed. Figures 3 and 4 show that at low temperatures (below 435 ℃), lateral oxidation of $Al_{0.98}Ga_{0.02}As$ follows a linear growth law, and at high temperatures approximately increasing parabolic growth is observed.

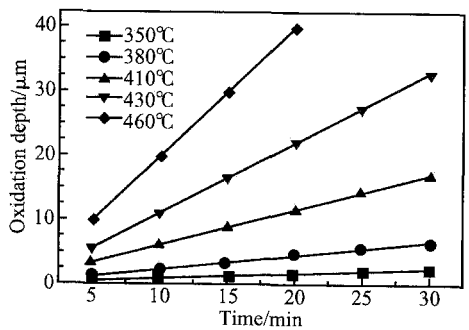

Fig. 2 Measured lateral oxidation depth versus time for the mesa with stripe at different temperatures

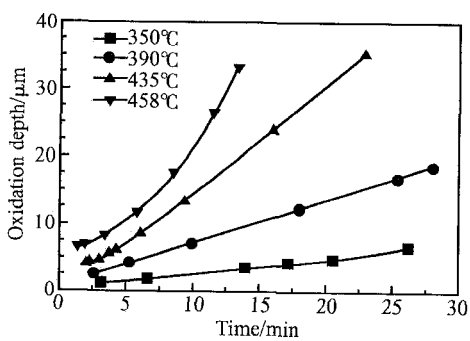

Fig. 3 Measured lateral oxidation depth versus time for mesa with RT at different temperatures

The observed difference of the oxide growth can be explained theoretically as follows.

In both circles and squares, the surface area of the oxidation front decreases as the oxidation proceeds, and this geometric effect causes an increase in the oxidation rate[10]. However, at relatively low temperatures the thermal movement of ions and molecules (O^{2-}, O_2, H_2O) is too slow to enable enough diffusion through the oxide. Thus the geometry of the mesa structures has little effect on oxidation rate. Conversely, at higher temperatures, there is an adequate supply of the reactant at the oxidation front in spite of the increasing oxide length. Thus, the geometry of the mesa has a significant effect on the time dependence of the oxidation process at higher temperatures.

We take the oxidation time to be the sum of the time required for reactant atoms to diffuse to the oxide-semiconductor interface and the time required for the atoms to react at that interface:

$$t_{oxidation} = t_{diffusion}(D, x_0) + t_{reaction}(K, x_0) \quad (1)$$

Here, K is the parameter relevant to the reaction rate, given in Eq. (3), and D is the diffusion constant for oxygen in the oxide film. The oxidation time can also be expressed as[10]

$$t = \frac{x_0}{K} + \frac{x_0^2}{k_D} \quad (2)$$

$$K = R/\rho\sigma \quad (3)$$

$$k_D = 4D[\mathrm{Erf}^{-1}(0.5)]^2 \quad (4)$$

Here, x_0 is the length of the oxide formed, R is the reaction rate (in units of atoms per unit time), ρ is the concentration of oxidant molecules in the oxide, and σ is the outside surface area of the oxidation front of the mesa. At low temperatures, k_D is very small and hence the second term on the right-hand side of Eq. (2) is very large, so K has no obvious effect on the total time t. Conversely, k_D is larger at higher temperatures and the first term in

Eq. (2) contributes noticeably to the total time t, i. e. , the effect of K on the total time t cannot be ignored. For a steady-state process, we assume R and ρ are constant at higher temperatures, i. e. , they are independent of the distance from the interface with the ambient. In the case of mesas with stripes, σ is a constant, but for mesas with RTs, σ decreases as the oxidation proceeds. According to Eqs. (2) and (3), the oxidation rate increases for mesas with RTs as the oxidation front approaches the center of the mesa. In the case of mesas with PRs, σ increases during the initial oxidation and then decreases from the maximum as the oxidation proceeds. This results in a drop in the oxidation rate for the first minute and then an increase afterward. Thus the geometry of mesa structures influences distinctly on the oxide growth rate at higher temperatures.

Figure 5 shows that the lateral oxidation is very sensitive to temperature. The lateral oxidation depth increases as the process temperature increases. Between 350 and 440 ℃, the oxidation rate increases by a factor of 10. Therefore, higher temperatures result in a substantial reduction in the oxidation time necessary to produce a required oxide aperture.

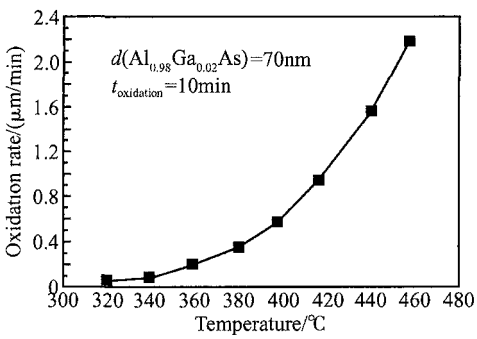

Fig. 5　Plot of oxidation rate versus temperature

Figure 6 shows the relationship between the carrier gas flow rate and the oxidation rate at 440 ℃. The water temperature was maintained at 92 ℃. The oxidation rate increases rapidly with increasing flow rate of the carrier gas in the small flow region. The oxidation rate then tends to remain constant, independent of the carrier gas flow rate. The threshold point is 1. 27L/ min. This means that in order to obtain an oxidation rate independent of the carrier gas flow rate, the carrier gas flow rate should be higher than 1. 27L/ min at 440 ℃.

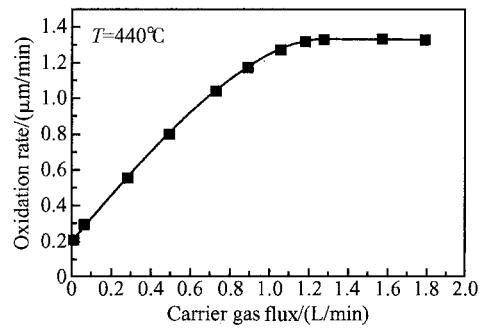

Fig. 6　Plot of oxidation rate versus the carrier gas flux

4　Conclusion

The characteristics of the lateral oxidation of $Al_{0.98}Ga_{0.02}As$ layers in VCSELs have been researched. The oxidation for stripe mesas follows a linear behavior. However, for the two geometry mesa structures we employed in VCSELs, oxide growth follows a linear law at low temperatures (below 435 ℃) and an increasing parabolic behavior influenced by the geometry of the mesa structures at higher temperatures (above 435 ℃). Theoretical analysis demonstrates that the geometry of mesa structures distinctly influences the oxide growth rate at higher temperatures. The oxidation is very sensitive to temperature. Between 350 and 435 ℃, the oxidation rate increases by a factor of 10.

References

[1] MacDougal M H, Dapkus P D, Pudikov V, et al. Ultralow threshold current vertical-cavity surface emitting lasers with AlAs-oxide-GaAs distributed Bragg reflectors. IEEE Photonics Technol Lett, 1995, 7: 229

[2] Hayashi Y, Mukaihara T, Hatori N, et al. Record low threshold index-guided InGaAs/ AlGaAs vertical-cavity surface emitting laser with a native oxide confinement structure. Electron Lett, 1995, 31: 560

[3] Lear K L, Choquette K D, Schneider R P, et al. Selectively oxidized vertical-cavity surface emitting lasers with 50 % power conversion efficiency. Electron Lett, 1995, 31: 208

[4] Choquette K D, Lear K L, Schneider R P, et al. Fabrication and performance of selectively oxidized vertical cavity lasers. IEEE Photonics Technol Lett, 1995, 7(11): 1238

[5] Ochiai M, Giudice G E, Temkin H, et al. Kinetics of thermal oxidation of AlAs in water vapor. Appl Phys Lett, 1996, 68: 1898

[6] Dong Limin, Guo Xia, Qu Hongwei, et al. Study on $Al_{0.98}Ga_{0.02}As$ wet oxidation. Chinese Journal of Semiconductors, 2005, 26(1): 197 (in Chinese) [董立闽, 郭霞, 渠红伟, 等. $Al_{0.98}Ga_{0.02}As$的湿法氧化规律. 半导体学报, 2005, 26(1): 197]

[7] Li Ruoyuan, Wang Zhanguo, Xu Bo, et al. Wet oxidation of

$Al_xGa_{1-x}As$/GaAs distributed Bragg reflectors. Chinese Journal of Semiconductors, 2005, 26(8): 1519

[8] Hao Yongqin, Zhong Jingchang, Xie Haorui, et al. A new process for improving performance of VCSELs. Chinese Journal of Semiconductors, 2005, 26(12): 2290

[9] Hao Yongqin, Zhong Jingchang, Jiang Xiaoguang, et al. A novel open-annulused-distributed-hole method for oxidation in vertical cavity surface emitting laser. Acta Armamentarii, 2004, 25(6A): 79 (in Chinese) [郝永芹, 钟景昌, 姜晓光, 等. 氧化物限制工艺中开环分布孔法研制垂直腔面发射激光器. 兵工学报, 2004, 25(6A): 79]

[10] Alonzo A C, Ceng X C, McGill T C. Effect of cylindrical geometry on the wet thermal oxidation of AlAs. J Appl Phys, 1998, 84(12): 6903

垂直腔面发射激光器中的侧向氧化

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摘要: 研究了垂直腔面发射激光器(VCSEL)的侧向氧化工艺及其特性. 发现对于条形台面, 氧化物生长遵循线性生长规律. 但对于在 VCSEL 中采用的两种结构, 氧化物的生长(温度高于 435 ℃)表现为非线性生长行为. 理论分析表明, 台面结构的几何形状对高温下的氧化速率产生了影响.

关键词: 侧向氧化; 量子阱; 垂直腔面发射激光器

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