Stable Single-Mode Operation of an 850-nm VCSEL with a Higher Order Mode Absorber Formed by Shallow Zn Diffusion

C. C. Chen, S. J. Liaw, and Y. J. Yang, *Member, IEEE*

Abstract—We report that an 850-nm vertical-cavity surface-emitting laser with a planar higher order mode absorber, formed by shallow Zn diffusion ($<0.3\ \mu\text{m}$), operated at stable single-mode over the entire drive current range. A device with a $5 \times 5\ \mu\text{m}^2$ absorber aperture and a $5 \times 5\ \mu\text{m}^2$ oxide confined active region showed a $\sim 0.8\ \text{mA}$ threshold and a mode suppression ratio of 40 dB. The modeling indicates that the higher order modes will be suppressed strongly due to the much larger threshold gain, compared to that of the fundamental mode as long as the Zn diffusion depth outside the $5 \times 5\ \mu\text{m}^2$ absorber aperture is over $\sim 0.2\ \mu\text{m}$, which agrees well with the experimental results.

Index Terms—850-nm vertical-cavity surface-emitting lasers, mode suppression ratio, single mode, Zn diffusion.

I. INTRODUCTION

VERTICAL-CAVITY surface-emitting lasers (VCSELs) [1], [2] have become important light sources for the optical data communication and the optical interconnects, due to their advantageous properties such as low-threshold current, low-divergence circular beam, one- and two-dimensional array formation, and inexpensive wafer fabrication. In recent years, the 850-nm VCSEL has been adopted in gigabit-Ethernet for local area network (LAN). Even the current gigabit-Ethernet only requires VCSELs operating in a multimode fiber network, the VCSELs with stable single-mode operation are still important for the applications in the higher data rate communication, optical storage, and printing systems. It has been realized that the modulation bandwidth, or speed, can be maximized by maintaining the VCSEL in stable single-mode operation [3], [4]. Here, we may define the stable operation as a lasing operation that the single-mode emission can be maintained over the entire drive current range above the threshold. Various VCSEL structures are fabricated, but only few devices exhibited stable single-mode emission. The etched mesa VCSELs usually operate in multimode, due to the strong index-guiding structure [2]. The typical ion-implanted VCSELs only maintain single-mode operation at lower current level [5]. The VCSEL with a passive antiguide region (PAR) [6] can operate at a stable single-mode at high currents, but the device fabrication required an organometallic chemical vapor deposition (OMVPE) regrowth which is relatively complicated. The recent developed oxide-confined VCSEL requires an oxide layer close to a node

Fig. 1. Schematic diagram of a VCSEL consisting of an absorber with an aperture d formed by selective Zn diffusion and an active region with a width D formed by oxidation.

of the standing-wave, and forming a small active region less than $3\ \mu\text{m}$ diameter, to have stable single-mode operation [7], which demands an accurate control on the epilayer growth and oxidation process. The VCSEL with an etched surface can perform single-mode operation up to five times the threshold current, but it also requires a critical control on the etched depth [8]. The VCSEL, with a top partially disordered mirror formed by selective Zn diffusion through the entire top distributed Bragg reflector (DBR) outside the masked area, can maintain stable single-mode operation, but the devices suffered from the large optical loss due to the high hole concentration in the deep zinc diffusion region ($\sim 2\ \mu\text{m}$). This results in either a higher threshold current and a lower output power [9], or no lasing with the mirror aperture less than $7\ \mu\text{m}$ [10]. In this letter, we report that a VCSEL with a higher order mode absorber formed by shallow Zn diffusion operated at single-mode over the entire drive current range with a minimum threshold current of $\sim 0.8\ \text{mA}$ and a maximum mode suppression ratio of 40 dB. The Zn diffused region was formed selectively outside the $5 \times 5\ \mu\text{m}^2$ masked area similar to the previous work [9] but with a much shallower diffusion depth ($<0.3\ \mu\text{m}$). This corresponds to less than 3 DBR pairs minimizing the optical loss for the fundamental mode, while preserving the absorption and forming an effective absorber of the higher order modes.

II. DEVICE STRUCTURE AND FABRICATION

The epilayer is a typical structure for oxide confined VCSELs, consisting of three GaAs–AlGaAs multiquantum wells (MQW) sandwiched by a 30-pair n -type and a 20-pair p -type $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$ – $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ layers with an $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layer just above the MQW for the oxidation. The completed device shown in Fig. 1 was fabricated in the following way: First a Si_3N_4 mask with 5×5 and $10 \times 10\ \mu\text{m}^2$ squares were formed on the sample, then the masked sample with a Zn_2As_3 source was sealed in an evacuated quartz ampoule and heated

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The authors are with the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C. (e-mail: yiyang@cc.ee.ntu.edu.tw).

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to 650 °C for only 1–8 min. This resulted in a Zn diffused region with a shallow diffusion depth (0.2–0.5 μm) outside the Si_3N_4 masked area which forms a higher order mode absorber. After the Zn diffusion, the sample was etched with a solution of $\text{K}_2\text{Cr}_2\text{O}_7:\text{CH}_3\text{COOH}:\text{HBr}$ (1:1:1) to form mesa/moat structure. The moats were etched with $\sim 1\ \mu\text{m}$ deeper than the MQW active layer to expose the $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layer, and isolate the devices electrically. Then, the sample was put in a 415 °C furnace with 90 °C H_2O vapor flowing to oxidize the exposed $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ to form a current confined active region. Following the oxidation, a 2000 Å SiO_2 film was deposited over the entire sample, and a $30 \times 30\ \mu\text{m}^2$ square window was opened on the top of mesa. At the final step, a Cr–Au film with a $15 \times 15\ \mu\text{m}^2$ window was deposited on the top and a Ge–Au film was deposited on the backside of the sample to form a *p*- and an *n*-type contact, respectively.

III. RESULTS AND DISCUSSION

Since the Zn diffusion was performed on the sample for a short time (< 8 min), the lateral diffusion length beneath the Si_3N_4 mask was very short ($< 0.2\ \mu\text{m}$) and the resulted dimension of the absorber (Zn diffused region) aperture was simply determined by the dimensions of the Si_3N_4 mask. The devices with the absorber apertures of 5×5 and $10 \times 10\ \mu\text{m}^2$ and the oxide confined active regions of 5×5 , 10×10 , and $15 \times 15\ \mu\text{m}^2$ were fabricated to investigate the aperture and active region size effect on the mode selection, respectively. It was consistently shown that almost 100% of devices with $5 \times 5\ \mu\text{m}^2$ absorber aperture exhibited stable single-mode operation, while the device with a $10 \times 10\ \mu\text{m}^2$ aperture showed a single-mode at lower current level, and multimode emission at higher current levels. The results also showed that mode behavior was independent of the oxide confinement size, which indicated that the mode property of this VCSEL was fully determined by the absorber aperture. Fig. 2(a) shows the light output and voltage versus current characteristics of a VCSEL with a $5 \times 5\ \mu\text{m}^2$ absorber aperture and a $5 \times 5\ \mu\text{m}^2$ oxide confined active region. Fig. 2(b) shows the corresponding emission spectra of the device at different current levels, indicating the device operated at a single-mode with a higher order mode suppression of better than 40 dB up to the maximum drive current where the output power saturated. The Zn diffusion was done on this device for only 3 min, resulting in a diffusion depth of $\sim 0.25\ \mu\text{m}$ which was measured from a scanning electron microscopy (SEM) micrograph. The threshold current of ~ 0.8 mA and an output power of ~ 0.8 mW were obtained, which were much better than that of the VCSEL with zinc diffusion through the entire top DBR [9]. The laser with a $5 \times 5\ \mu\text{m}^2$ absorber aperture was also in contrast to the previous work [10], in which the device with a $< 7 \times 7\ \mu\text{m}^2$ absorber aperture could not lase due to the optical loss in the Zn diffused region. Both these results indicated that the optical loss for the fundamental mode in this VCSEL with shallow Zn diffusion has been reduced significantly.

To understand the effect of the Zn diffusion depth on the mode control, the Zn diffusion was conducted on the devices with a

Fig. 2. (a) The typical light output and voltage versus current characteristics of a VCSEL with a $5 \times 5\ \mu\text{m}^2$ absorber aperture and a $5 \times 5\ \mu\text{m}^2$ oxide confined active region. The diffusion depth is only $\sim 0.25\ \mu\text{m}$ corresponding to 2 DBR pairs. (b) The emission spectra at different current levels. The single-mode operation with a higher order mode suppression of 40 dB is maintained from 2 mA (~ 1 mA above the threshold) up to 6 mA where the output power saturates.

Fig. 3. The calculated threshold gain G_{th} (solid line), as a function of the diffusion depth in the top DBR of the VCSEL. G_{th}/G_{th0} is the ratio of the threshold gain with Zn diffusion against that without diffusion. The light intensity (dot line), with a standing-wave pattern close to the top surface for a VCSEL without Zn diffusion, is also shown for reference.

$5 \times 5\ \mu\text{m}^2$ Si_3N_4 mask for 3, 5, and 8 min, resulting in the diffusion depths of 0.25, 0.5 and $1\ \mu\text{m}$, respectively. The results showed that all the devices exhibited stable single-mode, independent of the diffusion depth. The threshold gain versus the diffusion depth calculated on the VCSEL using a transmission matrix model is shown in Fig. 3. We assume the hole concen-

tration is $\sim 5 \times 10^{19} \text{cm}^{-3}$ [11] and use the equation for the free carrier absorption [12]

$$\alpha_{fc} = \lambda_o^2 e^3 N_a / 4\pi^2 c^3 n \epsilon_o (m_h^*)^2 \mu_h$$

where

- λ_o wavelength in free space;
- e electron charge;
- N_a concentration of acceptor;
- c light speed;
- n refractive index of the semiconductor;
- ϵ_o free space permittivity;
- m_h^* effective mass of holes;
- μ_h hole mobility, to find the optical loss which is dominated by the free carrier absorption α_{fc} in the Zn diffused region.

It can be seen that the threshold gain G_{th} increases rapidly from $\sim 850 \text{cm}^{-1}$ at zero diffusion depth to $\sim 2000 \text{cm}^{-1}$ at the diffusion depth of $\sim 0.1 \mu\text{m}$, then increases gradually and nearly monotonically with the diffusion depth. Since the fundamental mode mostly couples to the $5 \times 5 \mu\text{m}^2$ aperture area where no diffusion occurred while the higher order modes couple to the absorber (zinc diffused region) outside the aperture [13], the value at the zero diffusion depth is the threshold gain of the fundamental mode, while the rest represent that of the higher order modes with different diffusion depths. The calculated results show that the required threshold gain for the higher order mode will be at least two times larger than that of the fundamental mode, as long as the diffusion depth is over $\sim 0.25 \mu\text{m}$, resulting in an easy and reliable process for single fundamental mode selection, which agrees well with the experimental results.

IV. CONCLUSION

We have demonstrated that the VCSEL with shallow zinc diffusion can provide a simple structure for stable single-mode operation with a relaxed and reproducible process control.

Both discrete and large scale array VCSELs with low threshold single-mode operation can be readily fabricated with this structure.

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