Ultimate modulation bandwidth of 850 nm oxide-confined vertical-cavity surface-emitting lasers

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Abstract. Complex influence of photon lifetime (controlled by the mirror loss) and aperture size on the performance of 850 nm InGaAlAs oxide-confined vertical-cavity surface-emitting lasers (VCSELs) with fully doped AlGaAs-based distributed Bragg reflectors (DBR) was investigated. We find a tradeoff between photon lifetime and gain nonlinearity for maximizing the optical bandwidth, leading to the optimum aperture size close to 4-6 µm. In spite of the reduced photon lifetime (from 4 ps to 1 ps), the excess damping caused by the current-induced self-heating limits the ultimate modulation bandwidth for the given VCSELs design at 24-25 GHz. Further improvement in high frequency characteristics can be facilitated by decrease of the heat generation and improvement of the heat removal from the active region as well as by proper engineering of the scattering loss at the oxide aperture while keeping the low capacitance optimizing design of the oxide aperture.

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) emitting at 850 nm are widely used as low-cost high-performance light sources, in the mode of direct current modulation, for data communication systems over short distances and for the optical interconnects in high-performance computing systems [1]. The most important factor that limits modulation response is damping of the relaxation oscillation, which directly proportional to photon lifetime in optical microcavity, gain compression and inversely proportional to differential gain. During the last few years several approaches were suggested in order to maximize the resonance frequency by increase of the differential gain of the active region and decrease of the mode volume (controlled by aperture size) as well as on minimizing the chip parasitics [2-4]. The combination of these methods allowed an increase in the modulation bandwidth of short-wavelength VCSELs up to 20 GHz [5-6]. To overcome damping limitation, the reduction of the photon lifetime was proposed [7].

In this work we have analyzed complex influence of photon lifetime together with aperture size on the high-speed performance of 850 nm InGaAlAs oxide-confined VCSELs and realize the ultimate modulation bandwidth possible for the given VCSEL design.
2. VCSEL design

A conventional VCSEL geometry with two doped distributed Bragg reflectors (DBR) was used. The VCSEL epitaxial structure consists of an n-doped GaAs contact/buffer layer, a bottom $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ n-doped DBR, a 1.5$\lambda$-thick $\text{AlGaAs}$ optical microcavity with a strained $\text{InGaAlAs}$-based active region, a top $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ p-doped DBR, and a p-doped GaAs topmost contact layer (see figure 1). The active region consists of multiple narrow InGaAs quantum wells (QWs) with an average In-composition of ~7% sandwiched between high energy bandgap AlGaAs cladding layers to improve the differential gain of the active region and to suppress the thermal escape of nonequilibrium carriers. The QWs are placed in the antinode position of the optical field intensity to provide sufficient modal gain for lasing. The number and the thickness of the QWs as well as the barrier thicknesses were chosen to be narrow enough to reach the maximum possible optical confinement factor. To eliminate excess voltage drop and provide low resistance, compositional graded interfaces with modulated doping profiles were used in DBRs. The average doping concentration in the doped regions is about $2 \times 10^{18}$ cm$^{-2}$ for both carrier type. To maintain reasonable internal optical losses and provide low series resistance the doping of the DBR layers is reduced near the active region, where the electric field intensity is the highest.

![Figure 1. Refractive index and longitudinal mode profile versus the vertical coordinate for the 850 nm oxide-confined InGaAlAs VCSEL with a fully doped DBRs. Inset: the scanning electron microscopy image of the fabricated VCSEL.](image)

VCSEL chips used in this study are a result of the joint project between VI-Systems GmbH (Federal Republic of Germany) and Connector Optics LLC (St. Petersburg, Russian Federation). The VCSEL structures were grown on an undoped GaAs substrate using metal-organic vapor-phase epitaxy. Lasers with different mesa diameters were fabricated in the high-speed design using standard fabrication techniques including: optical lithography, metal and dielectric evaporation, dry and wet etching, selective wet oxidation, etc. The schematic cross-section of the processed 850 nm oxide-confined VCSEL with a ground-source (GS) pad configuration is shown in inset in figure 1. Light power-current-voltage characteristics and small signal modulation response ($S_{21}$) of lasers were measured in the range current-aperture size from 1.5 µm to 10 µm.

3. Results and discussion

The photon lifetime depends on the total optical loss and the effective length of the optical microcavity. On the one hand, a decrease in the quantum efficiency and the laser speed can be
expected in case of high optical loss [9]. On other hand, an increase in the microcavity length can drastically change the optical mode structure and increase the internal optical loss [10]. Since the mirror reflectivity is a quit sensitive not only to the mirror pairs, but also to the thickness of the top DBR layer, the mirror loss can be controlled by etching the top DBR.

However the reduction of top DBR reflectivity by consequent removing the mirror pairs is challenging issue in case of AlGaAs DBRs with compositional graded interfaces. Furthermore such approach requires rather deep etching which negatively affects the uniformity of carrier injection to the active region and the laser series resistance. The most promising approach is "shallow" etching of DBR surface layers. Figure 2 shows the top DBR reflectivity dependence as function of etch depth at lasing wavelength, calculated by transmission matrix method and taking into account free carrier absorption. By etching the surface of top DBR up to 70 nm, the mirror reflectivity can be adjusted within the range 96.5–99.5%. As a result, the total mirror loss can be easily changed from 0.3% up to 1.8% (at fixed bottom DBR reflectivity), reaching a local maximum at 70 nm. Note that such approach enable to investigate the static and dynamic characteristics for a fixed set of devices starting from the minimal mirror loss and ending the maximum mirror loss with step by step shallow etching of top DBR with subsequent measurements and, as a result, to eliminate the uncontrollable variations of the laser characteristics (caused by epitaxial and/or processing deviations) and to improve the validity of the experimental data.

![Figure 2](image-url)

**Figure 2.** Calculated top DBR reflectivity and corresponding total mirror loss as a function of etch depth into the top DBR of 850 nm InGaAlAs VCSEL.

Figure 3.a shows the maximum 3dB modulation bandwidth and the rate of damping rise (so called K-factor) as function of the aperture size for VCSELs with the low mirror loss (~0.3%). As expected, the 3dB modulation bandwidth increases with reducing the aperture size, but quickly saturates at 21 GHz for aperture diameters less than 7 µm. According to the $S_{11}$ data and the equivalent circuit model electrical, the parasitic cut-off frequency of the investigated VCSELs was found to be about 24 GHz over the entire measured current range, which means that the electrical parasitic has no significant impact on the VCSEL's high speed performance. Hence, the saturation of the 3dB modulation bandwidth can be associated to the thermal effects and/or the damping. The resulting K-factor is hardly depended on the oxide aperture and be in the range of 0.21-0.23 ns, indicating the crucial role of the photon lifetime. However the dynamic characteristic of the large aperture VCSELs are mainly limited by the self-heating effect, while the higher photon density (e.g. the higher...
resonance frequency) and the excess damping caused by the current-induced self-heating sets the intrinsic limit of the reachable modulation bandwidth for smaller aperture VCSELs (see figure 4.a).

![Figure 3](image.png)

**Figure 3.** Measured 3dB modulation bandwidth and K-factor as function of the oxide aperture size for 850 nm InGaAlAs VCSELs with low (a) and high (b) mirror losses at 20°C.

The increase of the mirror loss up to 1.8% results in the reduction of the photon lifetime to 1-1.2 ps, however a twofold drop of the K-factor was revealed for the wide-aperture VCSELs (see figure 3.b). Moreover, the ultrasmall aperture VCSELs demonstrate a 20% increase of the resulting K-factor. It can be explained by the domination of the gain nonlinearity in the damping coefficient. The gain compression factor was estimated to be in the range $1.5-2 \times 10^{-17}$ cm$^3$ for all apertures size and the mirror loss. Hence, the complex behavior of the K-factor can be attributed to the dramatic change in the differential gain. According to the dependences of the slope efficiency on the mirror loss, the internal optical loss increases significantly with the reduction of the aperture size: from 0.16% per round trip at 10 µm to 0.5% per round trip at 1.5 µm (see figure 4.b), which means that the free carrier absorption loss are dominated in the wide-aperture VCSELs, while the optical scattering loss from the oxide aperture itself occurs in the smallest devices. Moreover, as the aperture size is reduced, the current injection efficiency decreases rapidly from 73% down to 35% (due to excessive carrier leakage at high current density). The dramatic increase of the threshold current density with decreasing aperture size (from 1.1 kA/cm$^2$ at 10 µm to 30 kA/cm$^2$ at 1.5 µm) leads to the significant reduction of the differential gain (from $9.7 \times 10^{-16}$ cm$^2$ at 10 µm to $4.1 \times 10^{-16}$ cm$^2$ at 1.5 µm).
As shown in figure 3.b, the decrease of the photon lifetime leads to the increase of the maximum 3dB modulation bandwidth for the wide-aperture lasers, while the maximum 3dB modulation bandwidth of the ultrasmall aperture VCSELs drops to 20 GHz. The competing effects of the reduced photon lifetime and the reduced differential gain results in the ultimate modulation bandwidth of 24-25 GHz at oxide current aperture in the range of 4-6 µm. The further enhancement of the modulation bandwidth can be done by minimizing self-heating (low heat generation and efficient heat removal from the active region) and optimizing design of the oxide aperture (tradeoff between the optical scattering loss and the mode volume).

4. Conclusion

The combined impact of the photon lifetime and the aperture size on high-speed performance of 850 nm InGaAlAs oxide-confined VCSELs with fully doped AlGaAs DBRs was analyzed. The static physical properties of investigated lasers are determined from the static light power-current-voltage characteristics as function of the mirror loss. To clarify the limiting mechanism of high-speed performance, the dynamic parameters of each particular lasers were extracted from the small signal modulation response and microwave reflection measurements. It was found that the damping effect sets the intrinsic limit of the reachable modulation bandwidth with decreasing the aperture size. As a result, the maximum 3dB modulation bandwidth of lasers with low mirror losses quickly saturates at 21 GHz in spite of the significant reduction of the mode volume with decreasing the aperture size. However with increasing the mirror loss, the gain nonlinearity starts making a significant contribution to the K-factor. The gain compression is independent on the apertures size and the mirror loss for the given VCSEL design, while the dramatic increase of the threshold current density with decreasing aperture size results in significant reduction of the differential gain. The competing effects of the reduced photon lifetime and the reduced differential gain leads to an optimum oxide aperture range for the maximized modulation bandwidth.

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