Single-mode temperature and polarisation-stable high-speed 850nm vertical cavity surface emitting lasers

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Abstract. A new intracavity-contacted design to realize temperature and polarization-stable high-speed single-mode 850 nm vertical cavity surface emitting lasers (VCSELs) grown by molecular-beam epitaxy is proposed. Temperature dependences of static and dynamic characteristics of the 4.5 µm oxide aperture InGaAlAs VCSEL were investigated in detail. Due to optimal gain-cavity detuning and enhanced carrier localization in the active region the threshold current remains below 0.75 mA for the temperature range within 20-90°C, while the output power exceeds 1 mW up to 90°C. Single-mode operation with side-mode suppression ratio higher than 30 dB and orthogonal polarization suppression ratio more than 18 dB was obtained in the whole current and temperature operation range. Device demonstrates serial resistance less than 250 Ohm, which is rather low for any type of single-mode short-wavelength VCSELs. VCSEL demonstrates temperature robust high-speed operation with modulation bandwidth higher than 13 GHz in the entire temperature range of 20-90°C. Despite high resonance frequency the high-speed performance of developed VCSELs was limited by the cut-off frequency of the parasitic low pass filter created by device resistances and capacitances. The proposed design is promising for single-mode high-speed VCSEL applications in a wide spectral range.

1. Introduction
Vertical-cavity surface-emitting lasers (VCSELs) are widely used as low-cost high-performance light sources for data communication systems, optical interconnects and different sensors [1] for their unique characteristics such as small laser beam divergence, low threshold current, high speed properties, capability of fabricating dense 2-D laser arrays, and the testing on wafer level. New promising applications (such as atomic clock, gyroscope and etc.) have relatively demanding requirements on short-wavelength VCSELs: low power consumption, high frequency modulation
bandwidth, narrow linewidth, stable linear polarization, precise output wavelength, low relative intensity noise, high temperature stability [2]. VCSELs with ultra-small apertures show stable fundamental transverse mode operation, however their modulation bandwidth is limited due to strong current-induced self-heating caused by the large resistance and gain suppression caused by non-uniform transverse optical field distribution [3]. Moreover the combination of cylindrical symmetry and isotropic gain leads to polarization uncertainty and instability in conventional GaAs-based VCSELs [4]. The above mentioned issues are quite complex, and still actual in spite of a number of efforts.

In this work we have focused on developing a new design and reliable technique to realize temperature and polarization-stable high-speed single-mode VCSEL grown by molecular-beam epitaxy (MBE). We discuss design optimization problems and demonstrate first approbation of our approach for 850-nm range VCSELs based on InAlGaAs material systems.

2. VCSEL design

Both MBE and metal-organic chemical vapor deposition (MOCVD) are widely used for VCSEL production. MBE-growth of the traditional short-wavelength oxide-confined VCSEL design based on fully-doped AlGaAs distributed Bragg reflectors (DBRs) is rather complicated due to large number digitally-graded heterointerfaces and precise doping control. Serial resistance of MBE-grown doped DBRs is usually higher than for MOCVD-grown doped DBRs. The possible approach to overcome the mentioned problems is intracavity-contacted VCSEL design with undoped DBRs [5]. However conventional intracavity-contacted VCSELs with contact layers close to active region suffer from non-uniform current spreading across the aperture and high optical losses in doped contact layers caused by free-carrier absorption. To improve intracavity design we propose to insert a few pairs of doped DBR between active region and contact layers. In addition a top dielectric DBR can be used to increase the optical confinement.

![Image](image_url)

**Figure 1.** (a) Schematic cross-section of the oxide-confined InGaAlAs VCSEL with a dielectric DBR and intra-cavity contacts; (b) The scanning electron microscopy image of the fabricated VCSEL.

The VCSEL structures were grown on an undoped (001)-oriented GaAs substrate using MBE-systems. The epitaxial wafers consist of the top p'-GaAs contact layer, the short p-doped Al$_{0.15}$Ga$_{0.85}$As/Al$_{0.9}$Ga$_{0.1}$As DBR with a thin AlAs/AlGaAs aperture layer, the InGaAlAs -based active region, the short n-doped Al$_{0.15}$Ga$_{0.85}$As/Al$_{0.9}$Ga$_{0.1}$As DBR, the buried n-Al$_{0.15}$Ga$_{0.85}$As layer and the 30-pair undoped Al$_{0.15}$Ga$_{0.85}$As/Al$_{0.9}$Ga$_{0.1}$As bottom DBR. The active region consists of multiple narrow InGaAs quantum wells (QWs) with an average In-composition of ~10% sandwiched between high energy bandgap AlGaAs cladding layers to suppress the thermal escape of nonequilibrium carriers. 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 improve the temperature stability of lasers the resonance wavelength of cavity mode was red shifted from the QW photoluminescence peak at 20°C by nominally 15 nm. The average doping concentration in the doped
regions is about \(2 \times 10^{18} \text{cm}^{-2}\) for p-type and \(1 \times 10^{18} \text{cm}^{-2}\) for n-type, respectively. To maintain reasonable internal optical losses and provide low series resistance the intracavity contact layers were doped nonuniformly with higher level at nodes of optical field. To decrease the potential barrier height at DBR heterointerfaces, linear compositional digital-grading layers with modulated doping profile were used. 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, etc. Selective wet oxidation of AlGaAs materials was applied to create lateral confinement both for the injected current and the optical field. Top dielectric SiO\(_2\)/TiO\(_2\) DBR was formed by magnetron evaporation technology. The details of the VCSEL processing can be found in [6]. The schematic cross-section of the processed 850 nm oxide-confined 850 nm VCSEL with a ground-source-ground (GSG) pad configuration is shown in figure 1.

3. Results and discussion

3.1. Static device characteristics

Figure 3(a) shows the temperature evolution of the typical light output power-current-voltage (L-I-V) characteristics for the 4.5 µm oxide aperture InGaAlAs VCSEL. The maximum output power decreases from 2.4 mW at 20°C to 1.2 mW at 90°C, which is \(\sim 50\%\) of the value at 20°C. The maximum slope efficiency is hardly temperature-dependent and exceeds 0.56 W/A. According to figure 3(b) the threshold current exhibits a clear minimum around 60°C, but still remains below 0.75 mA in the whole temperature range, helping to maintain the large differential gain at elevated temperatures. We believe that the obtained high-thermal stability of our VCSELs can be associated to the optimized gain-cavity detuning and the improved carrier localization in the active region. Note that the investigated lasers demonstrate relatively low serial resistance (<250 Ohm) as comparing with MBE-grown 980 nm VCSELs with fully doped DBRs and similar aperture size [7].

![Figure 3](image-url)

**Figure 3.** The InGaAlAs VCSEL with a 4.5 µm oxide aperture: (a) Measured light-current-voltage characteristics at different temperatures; (b) Threshold current as a function of temperature.

The lasing spectra at different currents and temperatures for the 4.5 µm oxide aperture InGaAlAs VCSEL are presented in figure 4. Despite the efficient longitudinal mode selection, the strong index guiding effect in oxide-confined VCSELs usually requires much smaller aperture sizes for single-mode operation, especially at short-wavelength range. However the laser emits via the fundamental mode at ~850 nm and demonstrates side-mode suppression ratio (SMSR) more than 30 dB throughout the whole current and temperature range. Such effective single-mode operation at relatively large
The current aperture can be explained by the enhanced transverse-mode discrimination in case of thin tapered oxide aperture [8].

![Figure 4](image_url)

**Figure 4.** The InGaAlAs VCSEL with a 4.5 µm oxide aperture: (a) Lasing spectra at 20°C and different current; (b) Lasing spectra at 2 mA and different temperatures.

![Figure 5](image_url)

**Figure 5.** The InGaAlAs VCSEL with a 4.5 µm oxide aperture: (a) Extracted orthogonal polarization suppression ratio as a function of bias current at different temperatures; (b) Microscope image of fully processed VCSEL (top) and near-field pattern below threshold (bottom).

Figure 5.a shows the results of the polarization resolved light-current measurements for the 4.5 µm oxide aperture InGaAlAs VCSEL. As threshold is reached, polarization is immediately fixed along the [110] crystal axis with the orthogonal polarization suppression ratio (OPSR) over 20 dB. On the one hand, it can be attributed to the electro-optic effect in standard GaAs-based VCSELs grown on (001)-oriented substrate [9]. However, this mechanism is inherently unstable and the polarization can change its orientation relative to the preferred crystal axis with varying the bias current or the temperature [4]. On the other hand, no polarization switching in our VCSELs was observed through the entire current and temperature range. As can be seen in Figure 5.b, the oxide current aperture has a rhombus shape.
despite the cylindrical symmetry of the mesa-structure, since the oxidation rate in our technology process is not the same in the different crystal directions. Hence one supposed that this strong polarization stability is due to in-plane non-uniform current injection and anisotropic transverse cavity geometries.

3.2. Dynamic device characteristics
To get a deeper understanding of high-speed capabilities of the developed VCSELs, especially at elevated temperatures, the small signal modulation response \( S_{21} \) and microwave reflection \( S_{11} \) were measured in the range from 50 MHz to 30 GHz. Figure 6(a) demonstrates the measured modulation bandwidth (or 3dB-frequency) as a function of bias current at different temperatures. The maximum modulation bandwidth exceeds 13 GHz in whole temperature range. The modulation current efficiency factor (MCEF) is very temperature stable and beyond 10 GHz/mA\(^{1/2}\), which is a result of the optimized cavity—gain detuning and advanced VCSEL design.

![Figure 6](image)

**Figure 6.** Modulation bandwidth (a) and resonance frequency (b) versus bias current at different temperatures for an InGaAlAs VCSEL with a 4.5 µm oxide aperture.

To clarify the limiting mechanism of high-speed performance, the dynamic physical properties of investigated lasers were extracted by fitting procedure similar to that described in [10]. Figure 6(b) shows the temperature evolution of the extracted resonance frequency at different bias current. The large gain—cavity detuning prevents the decrease in the differential gain at higher temperatures and result in the high temperature stability of the D-factor. Note that the relaxation resonance frequency reaches values comparable to the maximum bandwidth at the high temperature, which can be associated with a noticeable damping. However the extracted K-factor for our VCSELs is less than 0.25 ns corresponding to a maximum intrinsic bandwidth more than 35 GHz in the absence of thermal and parasitic limitations. Together with the small values of damping factor it clearly indicates the minor limiting effect of damping even at high temperature and currents.

According to the \( S_{11} \) data and the equivalent circuit model electrical, the parasitic cut-off frequency of the investigated VCSEL was found to be about 9 GHz over the entire measured current range. These electrical parasitic have a major impact on the VCSEL's high speed performance.

4. Conclusion
New intracavity-contacted design with composite DBRs was proposed and applied for MBE-grown 850-nm VCSELs based on InAlGaAs material systems. Temperature and polarization-stable high-speed single-mode VCSELs with submilliamp threshold current, slope efficiency more than 0.56 W/A, SMSR > 30 dB and modulation bandwidth higher than 13 GHz in the whole temperature range of 20-
80°C were realized. The proposed design can be easily adjusted to the desired spectral range in the promising VCSEL applications.

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References
[1] Michalzik R 2013 VCSELs: Fundamentals, Technology and Applications of Vertical-Cavity Surface-Emitting Lasers (Berlin: Springer-Verlag)
[2] Serkland D et al. 2007 VCSELs for atomic sensors Proceeding of SPIE 6484 648406
[3] Liu Y, Ng W – C, Oyafuso F, Klein B, and Hess K 2002 IEE Proc.-Optoelectron 149 182
[4] Verschaffelt G, Panajotov K, Albert J, Nagler B, Peemers M, Danckaert J, Veretennicoff I and Thienpont H 2001 Polarisation switching in vertical-cavity surface-emitting lasers: From experimental observations to applications Opto-Electron. Rev. 9 257–268
[5] Huffaker D L, Deppe D G  1999 Intracavity contacts for low-threshold oxide-confined vertical-cavity surface-emitting lasers IEEE Photon. Technol. Lett. 11 934–936
[6] Maleev N A et al. 2013 Single-spatial-mode semiconductor VCSELs with a nonplanar upper dielectric DBR Semiconductors 47 7 993-996
[7] Mutig A et al. 2009 Temperature-Dependent Small-Signal Analysis of High-Speed High-Temperature Stable 980-nm VCSELs J. Sel. Topics Quantum Electron. 15 679–686
[8] Blokhin S A et al. 2006 Vertical-Cavity Surface-Emitting Lasers Based on Sub-Monolayer InGaAs Quantum Dots Journal Quantum Electronics 42 851–858
[9] Van Exter M P, Jansen van Doorn A K and Woerdman J P 1997 Electrooptic effect and birefringence in semiconductor vertical-cavity lasers Phys. Rev. A, Gen. Phys. 56 845–853
[10] Mutig A, Blokhin S A, Nadtochiy A M, Fiol G, Lott J A, Shchukin V A, Ledentsov N N, Bimberg D 2009 Frequency response of large aperture oxide-confined 850 nm vertical cavity surface emitting lasers Applied Physical Letters 95 131101