1060-nm Tunable Monolithic High Index Contrast Subwavelength Grating VCSEL
Thor Ansbæk, Il-Sug Chung, Elizaveta S. Semenova, and Kresten Yvind

Abstract—We present the first tunable vertical-cavity surface-emitting laser (VCSEL) where the top distributed Bragg reflector has been completely substituted by an air-cladded high-index-contrast subwavelength grating (HCG) mirror. In this way, an extended cavity design can be realized by reducing the reflection at the semiconductor–air interface using an anti-reflective coating (ARC). We demonstrate how the ARC can be integrated in a monolithic structure by oxidizing AlGaAs with high Al-content. The HCG VCSEL has the potential to achieve polarization stable single-mode output with high tuning efficiency. The HCG VCSEL shows a total tuning range of 16 nm around an emission wavelength of 1060 nm with 1-mW output power.

Index Terms—III-V semiconductor materials, microelectromechanical systems, semiconductor lasers, vertical cavity surface emitting lasers.

I. INTRODUCTION

UNABLE semiconductor lasers emitting at a wavelength of 1060 nm have potential applications within short-reach optical interconnects and optical coherence tomography (OCT) [1], [2]. Air-cavity tunable vertical-cavity surface-emitting lasers (VCSELs) enable the broadband tunability required for high-resolution OCT imaging and wavelength-division multiplexing for optical interconnects [2]. 102 nm tuning range at 1550 nm has been reported for air-cavity mechanically-tunable electrically-pumped VCSELs [3]. It is generally recognized that the tuning range can be extended by using an anti-reflective coating (ARC) at the air–semiconductor interface and has been implemented by using a monolithic inverted distributed bragg reflector (DBR) or micromachined low-refractive-index ARC [3], [4]. We show the first incorporation of a monolithic low-refractive-index ARC. Polarization stable output is desirable for OCT in order to amplify the output power of the VCSEL using semiconductor optical amplifiers. Polarization control can be achieved by using a subwavelength grating, which has been demonstrated in VCSELs where part of the DBR has been replaced by a high-index contrast subwavelength grating (HCG) [5]. Here we present a VCSEL with a bottom DBR, an ARC and a top HCG surrounded by air grown in a single epitaxial step. This demonstrates that a single layer HCG can fully replace the growth of a top DBR and further enable polarization control.

II. DEVICE STRUCTURE

The structure of the HCG VCSEL is shown in Fig. 1. The first part of the VCSEL structure up until the ARC is similar to that reported in [6] where strain-compensated InGaAs/GaAsP multiple quantum wells (MQWs) provide gain. To enable wavelength tunability part of the cavity is made up of an air-gap. In order to increase the tuning efficiency we use the extended cavity design where an ARC reduces the reflection at the air–semiconductor interface. By replacing the top DBR with an HCG mirror a stable output polarization can be ensured [5], [7]. The bottom reflector is a 35 pair silicon-doped n-Al0.9Ga0.1As/n-GaAs DBR with a Bragg wavelength \( \lambda_B = 1060 \) nm. The DBR is followed by a semiconductor cavity with an optical thickness of 1.77\( \lambda_B \). The MQW active region consists of 3 strained In0.3Ga0.7As wells with strain-balancing GaAs0.8P0.2 barriers. The position of the center quantum well is designed to be at the intensity anti-node at \( \lambda = \lambda_B \). The electric field magnitude is calculated using 1D rigorous coupled wave analysis (RCWA), by which also the nonzero reflection phase of the HCG is accounted for [8]. To ensure single transverse mode operation an Al0.98Ga0.02As layer is oxidized to create an aperture which is positioned close to the field node. A p-GaAs current spreading layer doped to 5 \times 10^{18} \text{ cm}^{-3} is used as intra-cavity contact to the pin-junction. The current spreading layer is followed by a Al0.98Ga0.02As layer later to be oxidized to an ARC at the
semiconductor-air interface. The as-grown thickness of the $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layer has been intentionally increased by 6.7% to account for shrinkage as the layer is oxidized to the final $\lambda_B/2$ optical thickness. Earlier experimental and numerical investigations show how an ARC can increase the tuning efficiency [3], [9]. The air-gap is defined using a 560 nm $\text{Al}_{0.52}\text{In}_{0.48}\text{P}$ layer as sacrificial material, with the thickness being determined such that the air-gap is $7/6 \cdot \lambda_B/2$ minus the HCG reflection phase equivalent propagation length. The final n-doped GaAs layer functions as the micro-electro-mechanical system (MEMS) as well as the HCG mirror, which allows to change the air-gap thickness by using electro-static force.

The growth is done on “2” n-doped GaAs wafers by using metal-organic vapor-phase epitaxy (MOVPE) with a rotating disk reactor (Emcore D-125 Turbodisc). The MEMS and HCG is patterned by e-beam lithography and Cl$_2$ dry etching using the negative resist hydrogen silsesquioxane (FOx-12) as a hard mask. We have designed the HCG to have broadband reflectivity around $\lambda_B$ for light with the electric field polarized perpendicular to the grating stripes and for this have chosen a duty cycle of 0.72, pitch of 460 nm and thickness of 280 nm. The MEMS mesa and oxidation mesa are both patterned by ultraviolet (UV) positive photolithography and wet etching. The $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ oxide aperture layer was oxidized in steam between the mirror and bottom substrate.

The as-grown thickness of the $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layer has been intentionally increased by 6.7% to account for shrinkage as the layer is oxidized to the final $\lambda_B/2$ optical thickness. Earlier experimental and numerical investigations show how an ARC can increase the tuning efficiency [3], [9]. The air-gap is defined using a 560 nm $\text{Al}_{0.52}\text{In}_{0.48}\text{P}$ layer as sacrificial material, with the thickness being determined such that the air-gap is $7/6 \cdot \lambda_B/2$ minus the HCG reflection phase equivalent propagation length. The final n-doped GaAs layer functions as the micro-electro-mechanical system (MEMS) as well as the HCG mirror, which allows to change the air-gap thickness by using electro-static force.

The growth is done on “2” n-doped GaAs wafers by using metal-organic vapor-phase epitaxy (MOVPE) with a rotating disk reactor (Emcore D-125 Turbodisc). The MEMS and HCG is patterned by e-beam lithography and Cl$_2$ dry etching using the negative resist hydrogen silsesquioxane (FOx-12) as a hard mask. We have designed the HCG to have broadband reflectivity around $\lambda_B$ for light with the electric field polarized perpendicular to the grating stripes and for this have chosen a duty cycle of 0.72, pitch of 460 nm and thickness of 280 nm. The MEMS mesa and oxidation mesa are both patterned by ultraviolet (UV) positive photolithography and wet etching. The $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ oxide aperture layer was oxidized in steam ambient to a nominal oxide aperture diameter of 8 $\mu$m.

The top laser anode and MEMS contacts were patterned by lift-off lithography with a Pd/Ge/Pt/Ti/Au metal stack [10]. This allows a contact to be made to both the p-doped laser anode and n-doped MEMS layer simultaneously. The bottom laser cathode was metallized by Ni/Ge/Au and both contacts alloyed by rapid thermal annealing (RTA). The final step is the definition of the air-gap through wet etching of the sacrificial layer [11]. The air-gap is necessary for the tunable wavelength design, but a highly single-mode polarization stable VCSEL can also be achieved by simply omitting the sacrificial layer since the low-refractive index AlO$_x$ will provide enough index contrast for the HCG. Figure 2 shows a scanning electron microscope (SEM) image of the finished VCSEL with the MEMS contact.
a short optical cavity. The 3 dB tuning range at 10 nm is shorter than the complete single-mode tuning range. The side-mode suppression-ratio (SMSR) is >40 dB for the 3 dB tuning range and drops due to a decrease in the peak intensity. From measuring the light-current characteristic at increasing voltage it has been found that the decline in output power is due to an increase in threshold current. Figure 5 shows the threshold to be minimum at \( V = 0 \). The tuning efficiency of 0.08 nm/nm is half the 0.16 nm/nm expected from simulation. A possible explanation is that the optical thickness of the ARC deviates from the nominal value. Gierl \textit{et al.} have demonstrated 0.14 nm/nm tuning efficiency by using an ARC, and we expect a higher tuning efficiency due to a shorter cavity length [3].

IV. CONCLUSION

We have demonstrated the first VCSEL where the top p-doped DBR has been completely substituted by a air-cladded HCG mirror. In this way the optical cavity can be extended by reducing the optical reflection at the semiconductor-air interface, which helps to increase the tuning efficiency. The first results for such a monolithic structure shows 10 nm wide 3 dB continuous tuning range for a voltage increasing to 30 V. Furthermore this is the first demonstration of monolithic integration of an anti-reflective coating with a MEMS HCG mirror.

ACKNOWLEDGMENT

The authors would like to thank D. Larsson for discussions on the device processing. They would also like to thank J. M. Kim for his work on AllnP growth.

REFERENCES