Design of a MEMS tunable mid-infrared VCSEL integrated on the SOI platform

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A widely-tunable mid-infrared vertical-cavity surface-emitting laser (VCSEL) structure based on Si-electronics-compatible processes and adhesive wafer bonding technology is suggested and numerically investigated. This hybrid laser consists of a silicon-on-insulator high-index contrast grating (HCG), a III-V active region and a distributed Bragg reflector (DBR). The HCG works as a highly-reflective mirror to replace the conventional bottom DBR. In this paper, an overview of the HCG design, VCSEL cavity design and the simulated device tunability is presented. In this context, the angle dependence of the reflectivity of the HCG is analyzed and a tuning range of about 100 nm and a wavelength tuning efficiency of 0.205μm/ μm are predicted for the device.

Introduction

Laser sources emitting in the near- and mid-infrared region has been attracting a lot of attention recently for security and environmental applications, since several important gases, like CO, CH_4, N_2O, etc. can be detected using this wavelength range [1]. For example, the wavelength range around 2.3 µm offers the first water absorption free spectral window for CO detection. Vertical-cavity surface-emitting laser (VCSELs) are good candidates for sources in this wavelength range, since it can provide valuable characteristics such as low power consumption, small beam divergence, wide tunability and cost-effective packaging. Among the III-V material systems, GaSb-based heterostructures are a perfectly suited semiconductor material for covering the 2 – 3 µm range. Recently, GaSb-VCSELs emitting at wavelengths around 2.3 µm have been demonstrated based on a monolithic [2] or hybrid [3] configuration, both containing thick and lossy semiconductor distributed Bragg reflectors (DBRs) which could be replaced by high-index contrast grating (HCG) reflectors. GaAs and InP-based VCSELs have been reported at respectively 0.85 and 1.55 µm using one or two HCGs as mirrors [4-6], however such a configuration has not yet been demonstrated in the GaSb system [7].

In this paper, we propose a widely-tunable mid-infrared electrically-pumped VCSEL structure based on a CMOS-compatible HCG mirror and adhesive wafer bonding technology. The silicon-on-insulator (SOI)-based HCG is analyzed by the rigorous coupled-wave analysis (RCWA) method. Furthermore, a two-dimensional finite-difference time-domain (FDTD) method is used to study the lasing properties.

VCSEL Integration Design

The suggested GaSb HCG VCSEL structure is shown in Figure 1, it consists of a III-V die bonded on a SOI-HCG. In this design the III-V contains an active region as well as a semiconductor DBR. The resonant cavity is formed between the DBR and the freestanding HCG. The fabrication of the designed SOI-HCG structures is based on a CMOS compatible process: 193 nm deep UV lithography is used to pattern SOI with a 220 nm thick silicon layer. Then the SOI die is etched in buffered HF solution to fabricate freestanding HCG. The integration of the III-V die on the freestanding HCG is realized by adhesive bonding using an ultra-thin Benzocyclobutene (DVS-BCB) layer as an adhesive bonding agent. After bonding, the GaSb substrate is removed and the VCSEL is processed. Specifically, good electro-optical confinement is achieved by selectively etching the 20 nm-thin InAsSb layer of the tunnel junction [8]. The VCSEL is then electrically contacted and the HCG can be electro-statically actuated using the intra-cavity contacts.

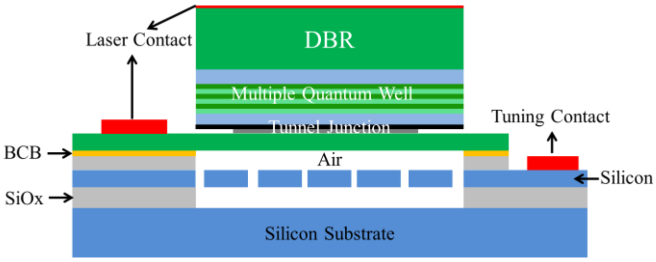

Figure 1: Schematic drawing of the tunable GaSb VCSEL integrated on SOI.

HCG Design

The SOI-HCG mirror structure is composed of a 220 nm thick sub-wavelength grating mirror on top of a silicon substrate as shown in Figure 2(a). Because some parameters such as the silicon layer thickness (220nm) and buried oxide thickness (2 µm) are fixed by the standard SOI technology, by playing with the grating period and duty cycle we can change the optical properties of the grating [9]. Figure 2(b) shows the reflectivity spectra simulated by the RCWA method of a SOI-HCG and typical 20-pair semiconductor DBR made of GaSb/AlAsSb. The HCG parameters used in this simulation are: period = 1.5 µm, duty cycle = 50%, the refractive index of the silicon is 3.48, air is 1 and the incident angle α is zero degree. No losses are considered in this simulation. Both the HCG and DBR exhibit high reflection in the range around 2.3 µm. For the HCG, a very broadband mirror with reflectivity >99% is obtained over the range 2.25 µm-2.38 µm as shown in the inset image of Figure 2(b). From this simulation it is clear that the HCG has a strong polarization dependence.

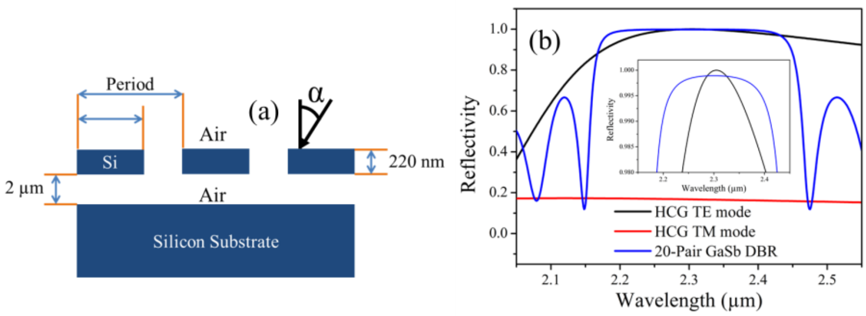

Figure 2: (a) Schematic drawing of the SOI-HCG structure, (b) reflectivity spectra of the SOI-HCG and the 20-pair GaSb-AlAsSb DBR.

Numerical simulations based on RCWA method were carried out to study the fabrication tolerance of different parameters in the HCG structure. The contour plot in Figure 3(a) shows the reflectivity of the HCG as a function of the period and duty-cycle for a fixed wavelength of 2.3 µm. We can see the duty cycle has around 30% fabrication tolerance while still keeping 99% reflectivity. Because the beam profile in VCSELs usually carries high incident angle components that are defined by the optical aperture, the design of the HCG dimensions should also consider the angle dependence of the reflectivity. As shown in Figure 3(b), the reflectivity and its incident angle dependence are plotted for varying duty cycles at a fixed HCG-period of 1.5 µm. The regions between DC= 25-30% and 50-55% shows a better angular dependence and a higher reflectivity (>99.9%) than the region around DC=40%. Since the high-order modes in a VCSEL have an angle divergence larger than 10°, HCGs are particularly interesting to enhance single-mode emission of VCSELs [4].

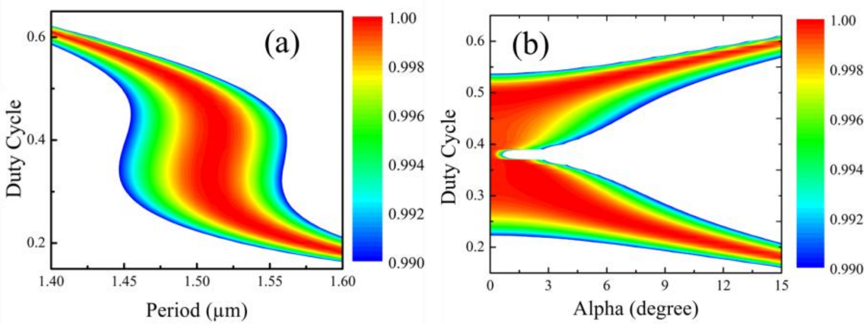

Figure 3: (a) RCWA simulated SOI-HCG reflectivity as a function of grating period and duty cycle for fixed λ = 2.3 µm, (b) contour plot of reflectivity versus duty cycle and incident angle.

Simulated Lasing Properties

The quality factor and the field distribution of the laser mode were investigated using the FDTD method. In this simulation, a Gaussian pulse is used to excite the cavity mode. The FDTD simulated resonant spectra shown in Figure 4(a) indicate a cavity resonance at 2.31 µm, and the estimated quality factor of this cavity mode is about 1600. The mode profile of this laser structure, shown in Figure 4(b), clearly shows that a strong vertical resonance occurs between the bottom HCG and top DBR.

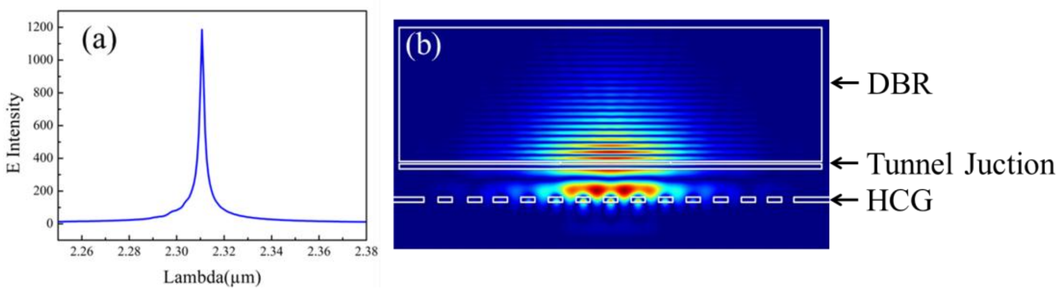

Figure 4: (a) FDTD simulated resonant spectra of the HCG GaSb VCSEL, (b) field profile of the resonant mode of the structure.

The vertical displacement of the HCG can change the optical cavity length, thus results in a change in the lasing wavelength [6]. So we can electro-statically actuate the HCG to tune the VCSEL emission wavelength. In order to increase the tuning efficiency, we can deposit a 200 nm SiNx antiflection layer (AR) layer on the n-GaSb layer. Figure 5 shows the resonant spectra and quality factor of the tunable VCSEL with AR layer as a function of the displacement of the HCG: by displacing the HCG 500nm, a wavelength tuning from 2.31 µm to 2.41 µm can be obtained. Therefore this structure has great potential for the realization of a widely tunable VCSEL. Over the whole wavelength range, the Q-factor of the cavity is calculated to be above 1300.

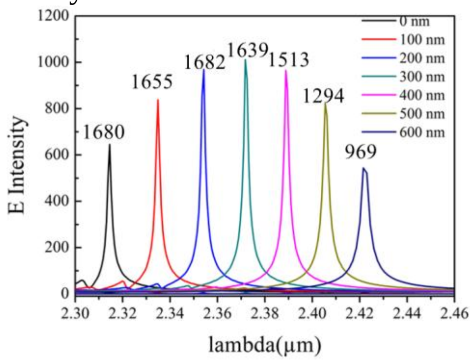

Figure 5: Resonant spectra of the tunable VCSEL versus movement of HCG.

Conclusion

In conclusion, we have suggested a hybrid laser structure for mid-infrared silicon photonics by integrating a GaSb VCSEL on an SOI grating. RCWA and FDTD simulation results show that the SOI-HCG can work as a highly-reflective mirror to replace conventional GaSb-based DBRs. This hybrid structure exhibits promising tunability and Q-factor characteristics suitable for a widely tunable VCSEL.

Acknowledgments

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