Two-dimensional integration of a vertical-cavity surface-emitting laser and photodetectors for position sensing

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1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) are the optical source of choice for many optoelectronic applications due to their low threshold, single longitudinal mode operation, and low beam divergence. The monolithic integration of VCSELs with photodetectors lends itself to a number of new applications. For example, a photodetector placed on top of a VCSEL can be used to dynamically monitor the laser output [1]. Monolithically integrated lasers and photodetectors can be used in a low cost optical transceiver component [2–5]. The integration of VCSELs with positive-intrinsic-negative (PIN) photodiodes can also be used in biomedical sensing [6]. For these and other applications, monolithic VCSEL and photodetector devices should exhibit high device uniformity and low optical and electrical crosstalk between devices on the same die.

Noninterfering and noncontact position sensing over long ranges with high precision has many applications. Lithography systems and other high precision positioning stages require accurate control and measurement of position. Traditionally, contact sensors and laser interferometric position measurement systems have been used to achieve high accuracy. For example, capacitance gauges have extremely high accuracy. However, their short range of operation requires the combination of other less accurate but longer range measurement devices. Laser interferometric position measurement systems and optical encoders [7] yield high-precision measurement over long ranges; however, they are costly, require accurate alignment, and can be difficult to miniaturize. Integrated VCSELs and detectors that monitor a signal reflected off of a grating can be used in position sensing and monitoring applications. As we demonstrate, the monolithic VCSEL–detector combination will have reasonably high precision and provide long range functionality while being a compact, low-power, and low-cost component.
Three types of detectors can be integrated with VCSELs: metal–semiconductor–metal (MSM) photodetectors [5], resonant cavity photodetectors (RCPDs) [2,3], and PIN photodetectors [1,4,6]. For the position-sensing application, small-area high-sensitivity detectors can be used to spatially resolve reflections from a corrugated surface. In this case MSM photodetectors are undesirable due to their lower detection area to device size ratio. RCPDs can have a larger detector area but suffer from their inherent spectral and angular sensitivity. They are not desirable because, even though the reflected light can be at the resonant wavelength of the detector, it will be directionally mismatched to the resonance of the cavity. PIN photodetectors are therefore chosen for this position-sensing application because of their intrinsically broad spectral response and high efficiency, low dark current, and compact integration with VCSELs.

Here the design, fabrication, and testing of a monolithically integrated VCSEL and PIN photodetectors in configurations applicable to position sensing are presented. We show simulations of the position-sensing capabilities that predict submicron resolution. We have developed a novel fabrication technique that incorporates a dry-etch process for precise definition of detectors. This process produces minimal damage to the VCSEL, and therefore high device uniformity is achieved. The optical crosstalk between VCSEL and detectors is also determined.

2. Simulation of Position Sensing

Figure 1 shows a sketch of the position-sensing scheme. The VCSEL in the center of the position sensor illuminates a metallic corrugation. The photodetectors around the VCSEL measure the light reflected off the corrugation back toward the die. As the corrugation moves parallel to the optical sensor, the measured power in each of the photodetectors changes, and the position of the corrugation relative to the sensor can be determined. Since the corrugation is periodic, this position-sensing scheme provides measurement for a long range of motion. Circuitry external to the VCSEL–photodetector combination can be used to record the number of grating periods that the corrugation has translated, making the maximum measurable translation of the sensor to be the physical extent of the corrugation.

Simulations in two dimensions were performed to diagnose the sensing capabilities of the integrated laser–detector configuration shown in Fig. 1. An integral method according to [8–10] was used to perform the calculation. These simulations focus on calculating the reflected field from the output of a VCSEL impinging on a periodic metallic corrugation. Microscope images of the VCSEL and detector configurations considered are shown in Fig. 2. The VCSEL at the center of each die has a mesa diameter of \(25 \mu m\). The translation direction considered is along a line that bisects the VCSEL and surrounding detectors. The light output from a VCSEL, with emitted wavelength \(\lambda\), was modeled as the lowest-order Gaussian beam, with beam radius of \(3\lambda\) (~5 \(\mu m\) diameter for the VCSEL emission at \(\lambda = 850 nm\)). The metallic corrugation was assumed to be a perfect electric conductor. A sawtooth triangular geometry was chosen for the metallic corrugation to model a typical commercially available grating. Figure 3 shows the backscattered electric field from a sawtooth corrugation of period \(4\lambda\), amplitude \(2\lambda\), and distance \(75\lambda\) from the laser source. The symmetric and antisymmetric corrugation placements correspond to the alignment of the corrugation node relative to the central axis of the VCSEL and a translation of the prior by a quarter of the grating period, respectively. It should be noted that these calculations do not take into account Fresnel reflection at the detector surfaces. The collected power for the various detector geometries in Fig. 2 can be found by spatially integrating the field intensities over the appropriate positions on each side of the VCSEL.

The total power incident on the innermost detectors as the corrugation translates to the right through one period is shown in Fig. 4. Figures 4(a)–4(c) correspond to the detector geometries shown in Figs. 2(a)–2(c), respectively. Here the vertical axis is the total power measured in a detector normalized to the total power emitted by the VCSEL. The translation distance of zero corresponds to the central axis of the VCSEL being aligned with a maximum (peak) of the corrugation. Note that approximately 47% of the VCSEL output power is reflected back toward the optical aperture of the VCSEL (in this case, a 9 \(\mu m\) diameter) and that this power varies by approximately \(\pm 3.6\%\) when the grating is linearly translated by one period.
The geometry of the detector pictured in Fig. 2(a) gives rise to a 58% variation in incident power during corrugation movement. Although this variation is relatively large, the overall incident power, and therefore measured signal, is small compared to the other two geometries. The detector geometries in Figs. 2(b) and 2(c) result in about one order of magnitude larger incident power but also a smaller overall power variation. The overall variation in the incident power in Figs. 2(b) and 2(c) is about 5% and 14%, respectively. For each detector geometry the incident power changes from its mean value to its maximum or minimum value after the corrugation has traveled approximately one quarter of the corrugation period, which would approximately correspond to the position sensing resolution. For the example calculated in Fig. 3, this would be 850 nm.

3. Sensor Design and Fabrication

The epitaxial structure of the integrated lasers and detectors is grown by metal organic vapor phase epitaxy. The VCSEL region is composed of a 35 period Al$_{x}$Ga$_{1-x}$As $n$-type bottom distributed Bragg reflector (DBR), a $1\lambda$ thick optical cavity with three quantum wells emitting at 850 nm, and a 20 period Al$_{x}$Ga$_{1-x}$As $p$-type DBR. Above the top facet of the VCSEL, a 100 nm thick In$_{0.49}$Ga$_{0.51}$P layer is placed to act as an etch stop for a chlorine-based reactive-ion etch process. The detector region consists of a 2 $\mu$m thick intrinsic GaAs absorption region between 270 and 300 nm $p$-type and $n$-type Al$_{x}$Ga$_{1-x}$As layers, respectively. Figure 5 shows a cross-sectional view of the fabricated devices.

Fabrication begins with the deposition of an $n$-type contact to define the detector cathode. The detector mesa is defined by reactive-ion etching (RIE). A 50:1 mixture of BCl$_3$ to Cl$_2$ produces high etch selectivity of AlGaAs/GaAs over In$_{0.49}$Ga$_{0.51}$P [11]. This allows for a precise and uniform etch stop on the In$_{0.49}$Ga$_{0.51}$P layer approximately 2.7 $\mu$m deep across the entirety of the wafer. The etch stop layer is then removed by chemical etching using a solution of either HCl:water or HCl:H$_3$PO$_4$ to expose the top facet of the VCSEL. The VCSEL anode contact is deposited, and the VCSEL mesas are etched using an inductively coupled plasma RIE with a SiO$_2$ etch mask. The current aperture of the VCSEL is defined by subsequent wet oxidation at 410 °C [12]. Because of the variable topology of the laser and detectors, a photo-definable polyimide was used to create a planar surface to facilitate bond pads around the periphery of each individual die. Lastly the edges of the bond pads and metal connections are encapsulated using a...
second layer of polyimide to improve the metal adhesion during wire bonding for component packaging.

The VCSEL mesas are fabricated with a nominal 9 μm diameter oxide aperture [12]. For the devices shown in Fig. 2(a), the separation between the VCSEL mesa and inner most detector is 17.5 μm, and the detector width and the detector-to-detector spacing are both 10 μm. In Fig. 2(b) the separation between the VCSEL mesa and detector is 20 μm, and the detector width is 100 μm. In Fig. 2(c) the separation between the VCSEL mesa and detector is 50 μm, the detector width is 75 μm, and the separation between detectors is 5 μm.

4. Device Characterization

A concern during fabrication is that the processing damage seen by the top facet of the VCSEL could lead to degraded laser performance [13]. Figure 6 shows the light versus current characteristics for 19 neighboring VCSELs with a 9 μm diameter oxide aperture. The fabrication procedure yielded excellent results with high device uniformity across a die. The average threshold current for the 850 nm emitting VCSEL is 0.52 mA with a corresponding average threshold voltage of 1.74 V. The average slope efficiency and maximum output power were measured to be 0.66 W/A and 6.7 mW, respectively.

Figure 7 shows the current versus voltage characteristic of a 406 μm diameter detector under different levels of illumination at 840 nm. In this experiment a power-calibrated fiber-coupled tunable laser was used to emit light at normal incidence to the detector surface, while the detector current was measured as a function of voltage. The turn on voltage and series resistance of the detectors are approximately 1 V and 22 Ω, respectively. The dark current measured with a 2 V reverse bias was approximately 40 nA for a 406 μm diameter detector. The average responsivity of the detectors was measured to be 0.38 A/W at 840 nm with a −2 V bias.

To understand the optical interaction between a VCSEL and detectors on the same sample, two detectors of the same size but different distance from the VCSEL are held at a constant bias voltage as the current in the central VCSEL is varied. The device geometry used in this experiment is that shown in Fig. 2(c). Figure 8 shows the absolute current measured in two adjacent detectors under a bias of −2 V as the current in the VCSEL is varied. Care
was taken to ensure that none of the VCSEL radiation was directed back toward the detectors. In Fig. 8 the solid curve corresponds to the laser light detected externally, and the dotted and dashed curves correspond to the absolute current in the closest and second closest detector, respectively. It can be seen that for the detector closest in proximity, the current increases rapidly until VCSEL threshold and then increases less rapidly to a maximum of approximately 3.4 μA near the VCSEL maximum output power. For the second closest detector, the trend is similar; however, the current reaches a maximum of only 0.25 μA.

Figure 8 indicates that the photodetector cross talk noise is dominated by detected spontaneous emission emitted through the sides of the VCSEL mesa [14]. The rapid increase of the photocurrent below threshold is indicative of the increasing spontaneous emission rate associated with increasing current injection. The slower increase of the detector current above threshold is due to the increase of spontaneous emission in gain regions not contributing to the VCSEL lasing modes [14]. Using the measured detector responsivity, the power measured in the closest detector for laser drive currents above threshold corresponds to approximately 0.2% of the total power in the VCSEL lasing mode. This is significantly less than the signal detected when this particular VCSEL–detector combination is used in the position-sensing scheme and will act only as a DC offset in the measured detector current.

5. Conclusion

We have fabricated and characterized monolithically integrated VCSEL and PIN photodetector devices for position sensing. We employ a novel fabrication process to achieve highly uniform laser characteristics over large wafer areas. Detector cross talk as a function of VCSEL current was measured and found to be approximately 0.2% of the VCSEL output power when the VCSEL was biased above threshold. Calculations indicate the feasibility of position sensing using a periodic corrugation. Future work will focus on characterization of the position-sensing capabilities as well as the determination of velocity, opening new applications for integrated VCSEL and photodetectors.

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References