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Polymer waveguide grating sensor integrated with a thin-film photodetector

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Abstract

This paper presents a planar waveguide grating sensor integrated with a photodetector (PD) for on-chip optical sensing systems which are suitable for diagnostics in the field and in-situ measurements. III–V semiconductor-based thin-film PD is integrated with a polymer based waveguide grating device on a silicon platform. The fabricated optical sensor successfully discriminates optical spectral characteristics of the polymer waveguide grating from the on-chip PD. In addition, its potential use as a refractive index sensor is demonstrated. Based on a planar waveguide structure, the demonstrated sensor chip may incorporate multiple grating waveguide sensing regions with their own optical detection PDs. In addition, the demonstrated processing is based on a post-integration process which is compatible with silicon complementary metal-oxide semiconductor (CMOS) electronics. Potentially, this leads a compact, chip-scale optical sensing system which can monitor multiple physical parameters simultaneously without need for external signal processing.

1. Introduction

Optical sensors are widely used in various sensing applications. In particular, optical sensors based on periodic grating structures [1–4] have been shown as promising sensing candidates because of their high sensitivity and intrinsic advantages of multi-parameter sensing [5]. For example, label-free chemical and biochemical sensing [6, 7] has been successfully demonstrated with high sensitivities. Multi-parameter monitoring [8] of strain, temperature, pressure, or vibration has been demonstrated for structural health monitoring.

Currently, most of the demonstrated grating-based sensors are based on optical fibers. While optical fiber based grating sensors have advantages for remote sensing applications, they have limitations on multi functional and analytical sensing applications. Recently, planar optical sensors [1, 9, 10] have been exploited to take advantages of integrating various functional devices in a single chip. Potentially, this approach will provide a robust, compact, on-chip sensing system that can monitor multiple physical parameters simultaneously without need for external signal processing.

In this paper, we introduce polymer-based Bragg grating sensor integrated with on-chip thin-film PD. This approach eliminates conventional external bulky read-out instruments and presents a potential on-chip micro sensor system with self-readouts. Based on a planar waveguide structure, the demonstrated sensor chip may incorporate multiple grating waveguide sensing regions with their own optical detection units. In addition, the demonstrated processing is based on a post-integration process which is compatible with silicon CMOS electronics. Therefore, the demonstrated approach can heterogeneously integrate optical sensing structures on CMOS based signal processing circuits. This allows a

complete on-chip sensor system which is suitable for diagnostics in the field and in-situ measurements.

2. Design and fabrications

Figure 1(a) shows the overall structure of the sensor that we implement. First, a thin-film InGaAs PD is heterogeneously integrated onto a SiO₂-Si substrate. And, an inverted polymer waveguide structure is fabricated on the substrate crossing the PD through standard photolithograph process. Then, we create submicron scale grating patterns on the polymer waveguide by using laser interference lithography. The electrical and optical performances of the fabricated sensor are characterized. In the following sections, the detailed fabrication and characterization of the sensor will be presented.

2.1. Fabrication and integration of thin-film PD and optical waveguide

Thin-film InGaAs metal-semiconductor-metal (MSM) PDs are grown, fabricated and optimized on a separate InP growth substrate. The growth InP substrate is removed to form a thin-film device structure using selective etching process. The as-grown PD material structure is as follows: InAlAs cap layer (Schottky barrier enhancement layer, 40nm)/ InGaAlAs graded layer (50nm)/ InGaAs absorption layer (500nm)/ InAlAs supporting layer (500nm)/ InGaAs stop etch layer (200nm)/ InP growth substrate. The interdigitated Schottky contacts (15nm Cr\ 130nm Au) were formed by dual-layer lift-off process and thermal evaporation. The MSM PD is 47 μ m finger long, with 2 μ m finger width and 3 μ m finger spacing and a detection area of 50 $\times$ 50 μ m². After metal definition, mesa structures (70 $\times$ 150 μ m²) are formed using H₃PO₄: H₂O₂: H₂O (1:1:40), which selectively stops at InP growth layer. Then, the mesa etched PDs are protected by Apiezon W wax and the growth InP substrate is selectively removed by using HCl: H₂O=2:1. After the substrate is removed from the PDs, the PDs are temporally bonded to a transfer diaphragm. The device thickness is around 1.1 μ m. An example of 1.1 μ m thick thin-film InGaAs MSM PD on a transfer diaphragm is shown in Figure 1(b). For the proposed integrated system, an integration substrate is prepared by thermally grown 3 μ m thick SiO₂ layer on Si substrates, which acts as an electrical insulation layer. Electrical contact pads (Cr\Au: 25nm\200nm) for PD integration are vacuum deposited and patterned on the substrate. Using the heterogeneous integration process [11], a thin-film InGaAs PD is inverted and integrated onto the contact pads on the substrate. After integrating the PD onto the substrate, 10min annealing at 150°C is performed to ensure stable gold metal to metal bonding. The topography of the integrated substrate is very flat since the PD thickness is only around 1.1 μ m. Figure 1(c) shows an inverted MSM PD integrated on electrical contact pads on SiO₂-Si substrate. Since the fingers of the integrated MSM PD face down and the back-side of the MSM PD faces on the surface of the substrate, the inverted MSM PD has eliminated conventional finger shadowing effect for front illumination, which degrades the sensitivity of the conventional MSM PD. This further enhances the sensitivity of the PD. Then, on the top of the substrate with the integrated thin-film PD, we fabricate optical waveguide structure using PMGI SF-11 and SU-8 polymer through a standard photolithography process. Figure 1(d) shows the top view of the grating region. The fabrication process flow of the optical waveguide structure is shown in Figure 2. We use SU-8 as the optical waveguide core material. First, SF-11 is applied on the top of the substrate, spread at 500 rpm for 15 seconds, and spun at 3000 rpm for 30 seconds. This creates a uniform layer of SF-11 with a thickness of 1.3 μ m. The sample is baked for 10 minutes at 190°C and allowed to cool down to room temperature (Figure 2(a)). And we pattern an AZ4110 layer with standard photolithography process on top of the SF-11 layer. First AZ4110 is spin-coated on top of the SF-11, spread at 500rpm for 15 seconds, and spun at 4000rpm for 30 seconds. The sample is baked for 60 seconds at 100°C and allowed to cool down to room temperature. Followed by 5 seconds of UV exposure at λ =365nm using a mask aligner (Karl Suss MJB3), and the sample is developed

with Microposit MF-319 developer. The structure is shown in Figure 2(b). Then, the sample is subsequently flood exposed at $\lambda=254\text{nm}$ for 3 minutes at $\sim 3\text{mW/cm}^2$. The SF-11 layer is developed by using the 101APG developer for 10 min as shown in Figure 2(c). Next, the AZ4110 layer is removed by rinsing the sample with acetone within 3 seconds as shown in Figure 2(d). Finally, SU-8 is spun and fully cured onto the SF-11 channel structure to form the inverted optical waveguide structure as shown in Figure 2(e). Figure 2(f) shows a scanning electron microscope image of the waveguide cross-sectional view. The estimated thickness of the SU-8 waveguide core is $2.3\mu\text{m}$. Since the top surface of the waveguide is flat as shown in Figure 2(f), this helps to make uniform grating patterns on the top of the waveguide structure as described in the next section. Based on the waveguide structural parameters and refractive indices of the waveguide materials ($n_{\text{SU-8}} = 1.57$ [12], $n_{\text{SF-11}} = 1.525$ [13], $n_{\text{SiO}_2} = 1.45$), optical mode analysis using COMSOL multiphysics [14] has been performed. The optical waveguide with $6\mu\text{m}$ width is estimated as a highly multi-mode waveguide with at least eight guiding optical modes. The optical propagation loss of the optical waveguide with $6\mu\text{m}$ is measured using the cut-back method [15]. The propagation loss is estimated to 3.63dB/cm as shown in Figure 3. The topology of the integrated PD with the optical waveguide is estimated by the surface profile measurement using Veeco Dektack 150 profilometer. Figure 4 shows the measured surface profiles from the outside area of the PD to the top of the PD. The measured step increment rate is slightly different depending on the scanning area. However, the step increment is less than $1.5\mu\text{m}$ over $150\mu\text{m}$ scan length, which represents a relatively smooth increment. The coupling efficiency from the waveguide to the integrated PD is theoretically estimated using two-dimensional bidirectional beam propagation method (BPM) [16]. The PD material parameters ($n = 3.595 - 0.075i$ at $\lambda = 1.55\mu\text{m}$) are obtained from a reference [17]. Waveguide core and PD thickness are set to $2.3\mu\text{m}$ and $1.1\mu\text{m}$, respectively. The PD length is set to $70\mu\text{m}$. However, to consider that the detection area of the PD is $\sim 10\mu\text{m}$ away from the mesa edge as seen in Figure 1(b), the coupling efficiency, which is expected to contribute the photocurrent of the PD, is estimated from $10\mu\text{m}$ away from the interface between input waveguide and the PD. The estimated coupling efficiency is $\sim 20\%$ using scalar BPM analysis. The current integration structure allows direct field coupling to the integrated PD. The structure can be further optimized to minimize the reflection at the integrated PD interface using a more optimized integration structure. An example of the optimized structure is shown in Figure 5(b) using a bottom cladding layer. In this structure, the PD is embedded in the bottom cladding layer with a certain separation from the waveguide core layer, which allows evanescent coupling to the integrated PD. Theoretically, this structure with varying the PD length can allow over 90% of coupling efficiency [16].

2.2. Grating fabrication and its characterizations

Lloyd's mirror configuration shown in Figure 6(a) is used to create grating patterns. It is composed of a mirror positioned perpendicular to a sample and a sample holder. An expanded beam illuminates both the mirror and the sample. Part of the light is reflected on the mirror, creating a virtual light source that effectively superimposes with the portion of the beam that is directly illuminating the sample. This superposition of the reflected and the expanded light waves on the sample creates a phase difference between the two waves. Waves that are in phase will exhibit a constructive interference while waves that are out of phase will undergo destructive interference, thereby creating grating patterns on the sample. The periodicity of such interference is varied by changing the angle of exposure. This is accomplished by rotating the sample holder relative to the incident laser beam. The formula for the desired grating period is given by

$$\Lambda = \frac{\lambda}{2\sin\theta}$$

Where Λ is the desired grating period, λ is the wavelength of the laser, and θ is the angle of the incident light beam as seen in Figure 6(a). The exposure set up consists of the Lloyd's mirror configuration in conjunction with an ultraviolet (UV) 30mW laser at $\lambda=405\text{nm}$, a polarizer, a spatial filter and a shutter.

To create grating patterns on a sample, S1805 positive photoresist is spin-coated at 5000 rpm. The thickness of the photoresist is around 500nm. After baking it at 110°C for 60 seconds, it is exposed in the Lloyd's mirror configuration. In the exposure process, the sample is positioned on the sample holder, as seen in Figure 6(a), perpendicular to the mirror and the angle is adjusted accordingly to the desired grating period. The shutter is opened to expose the sample for a pre-set amount of time. After the exposed sample is developed appropriately in a solution of Microposit MF-319 developer, the grating pattern appears. Typical developing time is less than 10 seconds. Figure 6(b) and (c) show a top view of grating patterns on a silicon substrate and a cross-sectional view of a sample with gratings, respectively.

The fabricated grating period is characterized by measuring the diffraction angle from the grating sample. Littrow configuration[18] has been used to measure the angle of the first order diffraction and subsequently determine the grating period. A grating sample is mounted on a rotational stage. After the grating sample is aligned to have the incident beam perpendicular to the sample, the first order diffraction angle is measured at the angle that the reflected beam from the first order diffraction is aligned with the incident beam. This allows us to measure the grating period of our fabricated samples.

For the demonstrated sensor, a grating area is locally defined on the waveguide region. To create a grating area on the specific locations of the waveguide pattern, we use a mask to define the grating area and other areas are exposed for 5 sec at 365nm. At this stage, the sample is not developed. Grating patterns are created by laser interference method on the unexposed S1805 area and followed by a develop process, which only leaves grating patterns on a defined waveguide area and removes S1805 on other exposed areas. Gratings are selectively defined on specific areas precisely on the top of optical waveguides.

3. Result and discussion

First, electrical characterization of the integrated PD is performed using a Keithley 2400 source measurement unit. Figure 7 shows the dark current and photocurrent of the integrated thin-film PD as a function of applied bias voltages. Measured surface-normal responsivity of the integrated PD is around 0.45A/W at the wavelength of 1550nm. To demonstrate the operation of the co-integrated sensor with optical waveguide grating device and on-chip PD, optical waveguide is designed to have 90 degree bending between input and output waveguide locations. The bending radius of the optical waveguide is 5mm. This configuration allows only coupled light in the waveguide to be measured properly. The period of the grating is chosen to be around 510nm to obtain its spectral reflection dip between 1500nm and 1700nm, which is covered by our tunable laser used for its optical characterizations. A schematic diagram outlining the simplified measurement configuration is shown in Figure 1(a). Optical light from a tunable laser (1500nm–1700nm) is butt-coupled using a single-mode optical fiber into an optical waveguide grating device. In the simple configuration as we fabricated, the grating works as an optical wavelength filter created by the periodic modulation of the effective refractive index of a waveguide. At a

particular wavelength, known as the Bragg wavelength, optical signal is strongly reflected and other wavelength of light is transmitted through the optical waveguide grating device. The thin-film PD is integrated right under the waveguides structure. The laser light is coupled and propagates through the waveguide structure and is directly coupled into an integrated PD, and electrical current from the PD is measured. Figure 8 shows the measured electrical current from the integrated PD when the wavelength of the coupled laser light is scanned. The grating area in the demonstrated sensor is 4mm. The measured Bragg wavelength from the integrated PD is around 1548 nm when the grating is exposed in air. The measured spectral dip has around 10dB of extinction ratio. As a demonstration of a refractive index sensor, a drop of de-ionized (DI) water is placed on the top of the grating area of the device. As expected, the spectral dip is moved to the longer wavelength at 1558 nm because of the increased refractive index of the top cladding from air to DI water. Thermal stability of the sensor will be limited by the polymer grating structure. Integrated thin film PD is thermally stable up to 270°C for 3 hours of annealing [19]. However, thermal stability of the grating structure formed by S1805 polymer expects to be limited up to around 120°C, which is the glass transition temperature of the polymer [20, 21].

4. Conclusions

This paper demonstrates co-integration of a polymer waveguide grating devices with a thin-film InGaAs MSM PD on a silicon substrate. Thin-film format of the PD provides an intimate integration of the PD with the waveguide grating device on silicon platform. Depending on the spectral needs of a detection system, different III–V semiconductor based devices can be selected and optimized for different measurement purpose and different wavelength range. The demonstration presented here offers an alternative approach for integration system for different optical functionalities.

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Figure 1.

(a) The structure of the integrated sensor chip. (b) Thin-film InGaAs MSM PD before integration. (c) Inverted thin-film InGaAs MSM PD integrated onto electrical pads on SiO₂/Si substrate. (d) Top view of the grating pattern area.

Figure 2.

Fabrication process flow of optical waveguide structure. (a) Substrate with one SF-11 layer. (b) AZ4110 patterning on SF11 layer and flood UV exposed at $\lambda=254\text{nm}$. (c) Develop SF-11. (d) Remove AZ4110 top layer. (e) SU-8 is spun and fully cured onto the SF-11 channel structure to form the optical waveguide structure. (f) Scanning electron microscope image of a cross-sectional inverted optical waveguide structure.

Figure 3.
Measured optical propagation loss using the cut-back method.

Figure 4. Measured surface profiles from the outside area of the integrated PD to the top of the integrated PD.

Figure 5. Cross-sectional waveguide and integrated PD coupling structure. (a) Direct coupling. (b) Evanescent coupling.

Figure 6. Laser interference exposure configuration. (a) Schematic Lloyd's mirror configuration. Scanning electron microscope images of top view (b) and cross-sectional view (c) of grating patterns.

Figure 7.
Measured dark current and photocurrent of an integrated inverted MSM PD.

Figure 8. Spectral characteristics measured through integrated thin-film PD of an optical waveguide with gratings exposed in air and DI water.