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Spectral Selective Mid-infrared Detector on a Silicon Platform

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Abstract: We report the design, fabrication, and characterization of spectral selective mid-infrared PbTe photodetector pixels monolithically integrated on a silicon platform. We demonstrate spectral selectivity with a peak responsivity of 65.4 V/W.

1. Introduction

Recently, people show increasing interest in spectral engineered mid-infrared (mid-IR) photodetectors due to their promising applications in chem-bio sensing and hyperspectral imaging.[1] Spectrally selective detection has been demonstrated by two typical structures: monolithic integration of narrow band filters and broadband infrared detectors.[2][3] and resonant-cavity-enhanced (RCE) photodetectors.[4-7] For the first type of detectors, incident IR light is modulated by filters and then absorbed by photosensitive layers, such as polycrystalline PbSe[2] or epitaxial PbTe films.[3] For the second type, photoactive layers, such as PbTe,[4][5] Pb1-xEu_xSe,[6] or HgCdTe,[7] are sandwiched between two one-dimensional photonic crystals (1d-PC), and thus a resonant cavity structure can be formed, providing highly wavelength-selective detection and high quantum efficiency even with much thinner absorber layer. Reduced bulk thermal generation and recombination noise, and higher operating temperatures can be achieved simultaneously. However, previous structures rely on either polycrystalline PbSe films, which needs high temperature sensitization process,[2][8][9] or expensive growth techniques such as molecular-beam epitaxy (MBE),[4-7] which lack the capability of being monolithically integrated with Si read-out integrated circuit (Si ROIC) due to backside illumination and substrate limitation. A low cost spectral engineered mid-IR photodetector technology that can be monolithically integrated on a Si platform still remains to be explored.

Our work leverages on such an RCE photodetection concept, using polycrystalline or amorphous films grown on a Si platform, thereby significantly reducing the cost and improving device robustness. Highly reflective 1d-PC and mid-IR photoconductive PbTe film without any sensitization process have been demonstrated separately in our initial work.[10] In this paper we report the design, fabrication and characterization of a mid-infrared photodetector with spectral selectivity and a peak responsivity of 65.4 V/W.

2. Design and fabrication

The design of cavity structure is based on transfer matrix method (TMM) and experimental data of optical properties of single layer films.[10][11] The cavity mode is designed to be at 3.7 μm. 4 periods is chosen for both bottom 1d-PC and top 1d-PC, which gives a Q value of 124.2.

Film deposition of Ge, As2S3, and PbTe is taken in the same chamber kept at room temperature. 2” diameter poly-Ge with Cu backing plate of 99.999% purity from Williams Advanced Materials is used as sputtering target, As2S3 bulk from Amorphous Materials Inc. and PbTe bulk of 99.999% purity from Alfa Aesar Inc. are used as the source material for thermal evaporation. Both the sputtering and the thermal evaporation are carried out at a base pressure of 5×10⁻⁷ Torr. Oxide coated Si wafers (6” Si wafers with 3 μm oxide, Silicon Quest International) are used as starting substrates. The substrates are held on a rotating substrate holder, at room temperature, throughout the depositions. Film deposition rate is monitored in real-time through a quartz crystal sensor and is maintained at 1.3 Å/s for Ge, and ~10 Å/s for As2S3 and PbTe.

Figure 1 shows the process flow to fabricate pixels. The pixel dimensions are defined by the width and distance of Sn metal contacts. The alignment is done using a Karl Suss Model MJB-3 Mask Aligner with a 350W Hg bulb. Negative photoresist is exposed to 320 nm UV light and developed to make openings for film deposition, which is followed by lift-off process in an ultrasonic bath.[12] Two lift-off steps are used to pattern top 1d-PC and Sn contacts separately. A 30 μm x 30 μm pixel is shown in Figure 2 to demonstrate the success of the above fabrication process.
3. Experimental results and discussion

Profilometry measurements performed on single-layer Ge, As$_2$S$_3$ and PbTe films yield excellent uniformity across an entire substrate with thickness variations < 3%. X-ray diffraction analysis on both Ge and As$_2$S$_3$ films confirms their amorphous nature, while the PbTe film features polycrystalline, face-centered-cubic (FCC) structure. Hall measurement performed at room temperature indicates the PbTe film is p-type, and has a Hall mobility of 64 cm$^2$/V/s and carrier concentration of 1.0E17 cm$^{-3}$.

Both transmittance and reflectance spectra are measured using a Nicolet Magna 860 Fourier Transform Infrared Spectrometer (FTIR) for the cavity structure, which is shown in Figure 3. In both spectra, the photonic band gap is clearly seen in the range of 3.0 μm - 4.4 μm. It is interesting to notice that the cavity mode is not shown in the transmittance spectrum, but shown in the reflectance spectrum at designed wavelength of 3.7 μm, indicating this portion of light is absorbed by the PbTe layer. The cavity mode has a full width at half maximum (FWHM) of 64 nm, which corresponds to a quality factor of 58. The agreement between experiment and design indicates excellent film thickness control and uniformity. However, Figure 3 also indicates a limited quantum efficiency of only 6% due to the present strongly under coupled cavity design. Through cavity design optimization to achieve critical coupling, at least one order of magnitude improvement in quantum efficiency and responsivity could be expected.

Glow bar light monochromatized through a sodium chloride prism is modulated at 10.3 Hz for the photoconductivity measurement. Due to the large bandwidth of the monochromator compared to the FWHM of the cavity mode shown in Figure 3, an external long pass filter is used to block all the light below 3 μm. Figure 4 shows the infrared responsivity of a 300 μm x 300 μm pixel at 1 mA bias current and at -60 °C cooled by a thermoelectric cooler (TEC). The peak responsivity is 65.4 V/W and locates at 3.9 μm, which agrees quite well with the design and the result in Figure 3. The peak in Figure 4 is very broad compared to the FWHM value of the cavity mode obtained by FTIR. This is because the fairly broad bandwidth of the incident light when the monochromator slit is tuned to be wider to enhance the incident
optical flux. With higher power IR light source and monochromator having better resolution, the responsivity peak could be located more accurately and the measured responsivity peak will become narrower.

![Graph showing infrared responsivity](image)

Fig. 5. Infrared responsivity of a 300 μm x 300 μm pixel at 1 mA bias current and at -60 °C cooled by a thermoelectric cooler (TEC). The peak responsivity is 65.4 V/W and locates at 3.9 μm, which agrees quite well with the design and the result in Figure 3. The responsivity peak is very broad compared to the FWHM value of the cavity mode obtained by FTIR. This is because the fairly broad bandwidth of the monochromator.

4. Conclusion
Spectral engineered mid-IR photoconductive pixels on Si platform have been designed, fabricated, and characterized. Monolithic integration of one-dimensional photonic crystal and thermally evaporated PbTe film on a Si platform has been demonstrated. The cavity mode around 3.7 μm is demonstrated by both FTIR and photoconductivity measurements.

Acknowledgements
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References
[1] Commercial gas sensors based on infrared absorption analysis are, e.g., Smart IR Ex P/N 6810460 from Draeger Sensor®.