Visible-Wavelength Chip-Scale Polarization-Sensitive Spectrometer Using GaN Photodiodes

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Abstract: A chip-scale spectrometer is proposed to resolve linear polarization information in the visible-wavelength range. The design was supported with preliminary experimental data based on elliptical cross-section nanopillar-shaped GaN photodetectors.

Chip-scale visible-wavelength spectrometers have been rapidly developed in recent years owing to their potential applications in bio and chemical sensing. Among various designs, reconstructive spectroscopy using a series of broadband photodetectors and computational spectral reconstruction has proven to be a powerful technique to simplify the hardware design and increase the spectroscopic system's tolerance to manufacturing and environmental variations [1]. Using GaN-based photodetectors, we have previously reported an on-chip spectrometer without needing external optics [2]. Deep learning with synthetic data has been used to create an inference network requiring minimal runtime computational resources [3].

A spectrometer capable of reconstructing polarization information can provide additional sensing modality. For example, polarization-sensitive hyperspectral imaging can overcome the limitation of regular dermal imaging techniques in pigmented legions or darker skins [4]. In this work, we have proposed and completed preliminary experiments to support the design of an on-chip polarization-sensitive spectrometer based on a similar reconstructive spectroscopy technique and GaN photodetectors with built-in structural asymmetry.

The polarization sensitivity is enabled by an elliptically shaped cross-section for the nanopillar photodetector, as shown in Figure 1(a). Each detector consists of an array of nanopillar photodiodes formed by patterning a commercial LED epi wafer using lithography and etching. The cross-sectional shape of each nanopillar is elongated in one direction with a 3:1 aspect ratio. The InGaN/GaN multiple quantum wells (MQWs) serve as the photocurrent-generating active region. A 10-nm thin conformal platinum (Pt) overlayer was used as the p-contact. A 10-nm thin SiO_2 layer was deposited between Pt and GaN for electrical insulation [5]. The asymmetric strain field in the MQW region creates elliptically shaped electron and hole wavefunctions, which absorb the light in different polarizations with different efficiencies. This was confirmed experimentally by measuring the photodetector's responsivities for two different light polarizations, as shown in Figure 1(b). The result shows that light absorption is more efficient when the polarization is parallel to the ellipse's long axis. We repeated the measurement with the sample rotated 90 degrees to confirm that different responsivity indeed originates from the structural asymmetry.

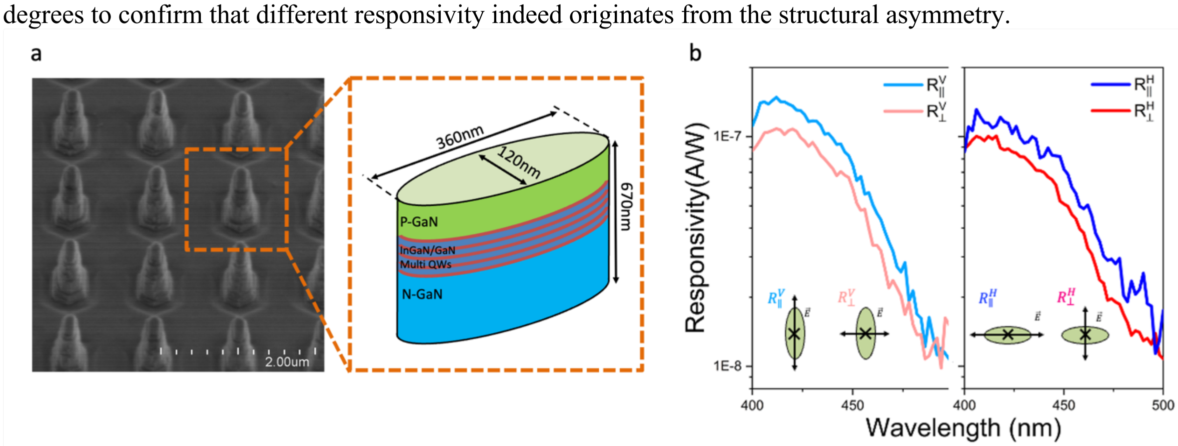

Figure 1 (a) Scanning Electron Microscope (SEM) image of a GaN-based photodetector consisting of an array of nanopillar photodiodes with elliptically shaped cross-sections. (b) Measured photodetector responsivities at a 0V bias as a function of the incident light's polarization. The notations follow the following convention: V (vertical) and H (horizontal) are referenced to the ellipse's long axis's direction from the top view; R^V *and* R^H *are responsivities of the vertically- and horizontally-oriented nanopillar photodiodes, respectively;* ∥ *and* ⊥ *represent the relationship between the light's polarization and the ellipse's long axis: parallel and perpendicular.*

In the following, we describe the design principle of a polarization-sensitive on-chip spectrometer based on reconstructive algorithms. The design consists of a series of 16 nanopillar broadband photodetectors with properties given in Ref. [2]. The dimension of the nanopillars controls and gives a different spectral response. We assume each photodetector responds to the incident light's polarization according to the experimental data given in Figure 1(b).

We denote the incident light's spectral intensity as $P(\lambda) = P_V(\lambda) + P_H(\lambda)$ where λ is the wavelength, and the subscripts V (vertical) and H (horizontal) use the convention defined in the caption of Figure 1(b). The photocurrent of each photodetector can be written as

$$I_{V,H} = \sum_{\lambda} R_{\parallel,\perp}(\lambda) P_V(\lambda) + R_{\perp,\parallel}(\lambda) P_H(\lambda)$$
$$= \sum_{\lambda} 0.5 R_{\parallel,\perp}(\lambda)(\mathrm{DoP}+1)P(\lambda) - 0.5 R_{\perp,\parallel}(\lambda)(\mathrm{DoP}+1)P(\lambda) + R_{\perp,\parallel}(\lambda)P(\lambda) \quad (1)$$

where the degree of polarization (DoP) is defined by $\mathrm{DoP}(\lambda) = (P_V(\lambda) - P_H(\lambda))/(P_V(\lambda) + P_H(\lambda))$.

To reconstruct the spectrum's two polarization components $P_V(\lambda)$ and $P_H(\lambda)$, we first reconstruct the spectral intensity $P_{guess}(\lambda)$ using the non-negative least square (NNLS) algorithm:

$$\min_{P_{guess} \geq 0} \parallel \left(R_{\parallel}(\lambda) + R_{\perp}(\lambda)\right) P_{guess}(\lambda) - (I_V + I_H) \parallel^2 \quad (2)$$

Once we obtain $P_{guess}(\lambda)$, we can reconstruct the polarization information using a least square algorithm:

$$\min \left[\left(R_{\parallel}(\lambda) - R_{\perp}(\lambda)\right) diag\left(P_{guess}(\lambda)\right)\mathrm{DoP}(\lambda) - (I_V - I_H)\right]^2 \quad (3)$$

The photodetector shown in Figure 1 has a Degree of Asymmetry ($DoA = |(R_{\parallel} - R_{\perp})/(R_{\parallel} + R_{\perp})|$) in the range of 0.1 ~ 0.2. We studied the spectrometer's performance using the lower bound of the experimentally measured DOA 0.1. The results are shown in Figure 2. Figure 2(a) shows the performance of reconstructing a single gaussian peak with an FWHM of 25 nm. Figure 2(b) shows the performance of reconstructing the DoP at three different wavelengths: 450, 550, and 620nm. It can be observed that the DoP reconstruction is only satisfactory when the intensity spectrum can be reconstructed accurately first. Figure 2(c) shows the reconstructed DoP's accuracy as a function of the wavelength. The DoP's reconstruction accuracy is compared between using the reconstructed intensity spectrum $P_{guess}(\lambda)$ and the ground truth $P_{true}(\lambda)$. It can be seen that the DoP can be accurately reconstructed if the intensity spectrum's reconstruction performance can be improved. But even with the existing $P_{guess}(\lambda)$, the accuracy is around 90% or better in the wavelength range of 400 – 590 nm.

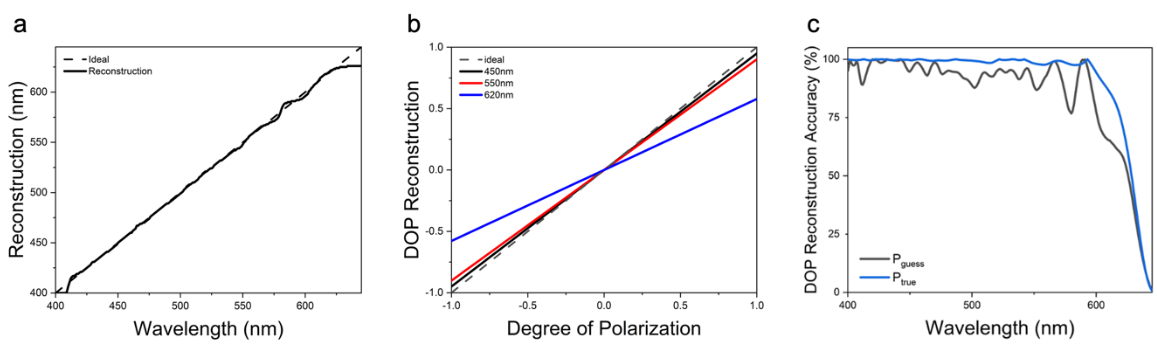

Figure 2 Spectral reconstruction performance: (a) Reconstruction of a single gaussian peak (FWHM = 25nm) using an NNLS algorithm. (b) DoP reconstruction at 450, 550, and 620nm as a function of the incident light's DoP. (c) DoP reconstruction as a function of the wavelength with a constant DoP for the entire wavelength range. Reconstruction is compared between using an NNLS-reconstructed intensity spectrum $P_{guess}(\lambda)$ and with the ground truth $P_{true}(\lambda)$.

In summary, a polarization-sensitive chip-scale spectrometer without the need for any external optics is proposed. The design's performance was evaluated based on the experimental measurement of a GaN-based photodetector's responsivity as a function of the incident light's linear polarization.

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