UV-VIS Chip-Scale Spectropolarimeter

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ABSTRACT

An on-chip spectropolarimeter is proposed based on gallium nitride polarization and spectral encoders. Polarization encoding is achieved via local strain engineering and valence-band mixing induced by asymmetric strain relaxation. Broadband polarization-sensitive photodetectors can replace linear polarizers to enable chip-scale implementation of a spectropolarimeter with the help of computational reconstructive algorithms.

Keywords: spectroscopy, polarimetry, deep-learning, compressive sensing, gallium nitride

1. INTRODUCTION

Computation spectroscopy has emerged as a powerful technique to miniaturize a conventionally bulky spectrometer system [1]. This work proposes a compact chip-scale spectropolarimeter based on reconstructive algorithms and local strain engineering in gallium nitride (GaN) semiconductor nanostructures [2]. While a spectrometer measures an optical signal's intensity, a spectropolarimeter can obtain extra information, such as the electric field's polarization and phase. Spectropolarimetry is an essential tool for sensing, providing a wealth of new information not available from a conventional spectrometer. A standard spectropolarimeter utilizes polarization optics, including linear polarizers and wave plates. We will show that polarization-sensitive photodetectors can replace linear polarizers to enable chip-scale implementation. Moreover, the computational approach can leverage deep learning to considerably reduce the computational resources required during operations [3].

2. DEVICE DESIGN

Figure 1(a) shows the proposed device structure in this study. The device consists of an array of GaN photodetectors. The building block for these detectors is a nanopillar-shaped GaN light-emitting diode (LED) but left biased such that the active region can absorb light and generate photocurrent. The nanopillar LED's size (diameter) and shape can be designed to change the detector's spectral responsivity [2]. As a result, the input optical signal is encoded differently by different photodetectors. The signal's spectrum can be reconstructed based on the pre-calibrated spectral responsivity curves. Although a unique solution is only possible when the number of detectors is the same as the signal's degree of freedom, e.g., the number of wavelengths, regularizers can be imposed to select the "most likely" spectrum even with a small number of detectors, enabling the miniaturization of the spectrometer system.

The photodetectors need to generate a photocurrent sensitive to the optical signal's polarization to obtain the polarization and phase information. This can be achieved using a nanopillar LED with an elliptical cross-section, as shown in Figure 1(a). The elliptical cross-section generates an asymmetric strain profile in the LED's active region. Because GaN's heavy hole, light hole, and split-off bands are closely spaced from each other, the asymmetric strain mixes the valence bands differently along the ellipse's major- and minor-axis directions and results in a linearly-polarized emission at a low-temperature and low-excitation condition [4]. The emission's degree of linear polarization (DLP) quickly degrades with an increasing temperature and higher electron-hole concentration in the active region [5]. As the polarized light emission is due to the strain-modified valence bandstructure, the optical absorption is also expected to be sensitive to the light's polarization.

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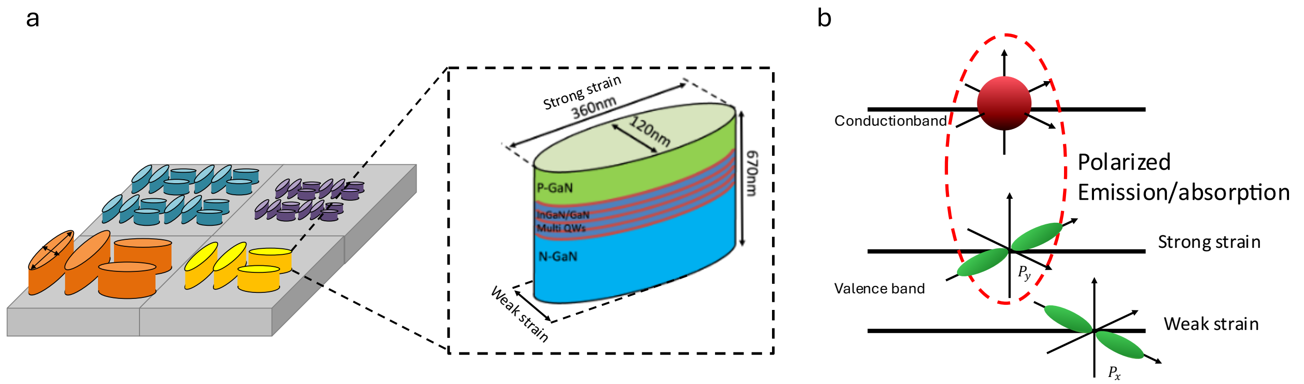

Figure 1 (a) Device design for an array of GaN photodetectors enables simultaneous spectrum and polarization reconstruction. The callout shows a typical building block, a nanopillar-shaped GaN LED with an active region consisting of multiple compressively-strained quantum wells. The nanopillar's size (diameter) and shape can be controlled by lithography and etching. (b) The schematic of valence band mixing in the LED's active region due to the asymmetric strain profile, leading to polarized light emission and optical absorption's polarization sensitivity.

Assuming the optical signal's electric field can be described by

$$\vec{E}(\lambda) = |E_H(\lambda)|\hat{H} + e^{-i\Delta\phi(\lambda)}|E_V(\lambda)|\hat{V} \tag{1}$$

where $\{\hat{H}, \hat{V}\}$ is a linear polarization basis. We consider a pair of photodetectors with their respective building block's ellipse's major axes orthogonal to each other. Without the loss of generality, we choose the polarization basis such that $\hat{V}$ is parallel to one of the photodetector's ellipse's major axis. We denote the photocurrent generated from this photodetector as I^V. The photocurrent generated from the other photodetector will be denoted as I^H. We also assume the photodetector's spectral response is polarization sensitive, described by $R_{\parallel}(\lambda)$ and $R_{\perp}(\lambda)$, respectively. $R_{\parallel}(\lambda)$ and $R_{\perp}(\lambda)$ are the spectral responses when the light's polarizations are parallel to the ellipse's major and minor axes, respectively. We can write:

$$I^{V,H} = \sum_{\lambda} R_{\parallel,\perp}(\lambda)|E_V(\lambda)|^2 + R_{\perp,\parallel}(\lambda)|E_H(\lambda)|^2 \tag{2}$$

The reconstruction of the optical signal's spectrum and polarization follows three steps. The first step is to reconstruct the spectral power distribution ($P(\lambda) = |E_H(\lambda)|^2 + |E_V(\lambda)|^2$). The second step calculates the DLP, defined as $DLP(\lambda) = \frac{|E_V(\lambda)|^2 - |E_H(\lambda)|^2}{|E_V(\lambda)|^2 + |E_H(\lambda)|^2}$. The final step reconstructs the phase $\Delta\phi(\lambda)$ between $E_H(\lambda)$ and $E_V(\lambda)$.

Equation (2) can be rewritten in terms of DLP as follows.

$$I^{V,H} = \frac{1}{2}\sum_{\lambda} R_{\parallel,\perp}(\lambda)(\mathrm{DLP}(\lambda) + 1)P(\lambda) + R_{\perp,\parallel}(\lambda)\big(1 - \mathrm{DLP}(\lambda)\big)P(\lambda) \tag{3}$$

Adding I^V and I^H in (3) eliminates the DLP dependence and allows us to determine the spectrum using a reconstructive algorithm, e.g., the non-negative least square (NNLS) algorithm as follows.

$$\min_{P_{guess} \geq 0} \parallel \Big(R_{\parallel}(\lambda) + R_{\perp}(\lambda)\Big) P_{guess}(\lambda) - (I_V + I_H) \parallel^2 \tag{4}$$

Once the spectrum $P_{guess}(\lambda)$ is reconstructed, we can determine the DLP using a least-square algorithm by subtracting the two photocurrents in (3):

$$\min_{1\geq DLP(\lambda)\geq -1} \left[\left(R_{\parallel}(\lambda)-R_{\perp}(\lambda)\right) diag\left(P_{guess}(\lambda)\right)\mathrm{DLP}(\lambda)-(I_V-I_H)\right]^2 \tag{5}$$

Finally, a birefringent thin film can be added to reconstruct $\Delta\phi(\lambda)$. The thin film will be deposited on another pair of photodetectors. The film's thickness does not need to be precisely controlled or sufficiently thick to become a quarter- or half-wave plate. To illustrate the process, we assume the birefringent thin film's fast axis is aligned at 45 degrees relative to $\hat{H}$. After the optical signal passes through the thin film, we have

$$|E_H'|^2 = \cos^2(\eta/2)\,|E_H|^2 - \sin(\eta)\sin(\Delta\phi)\,|E_H||E_V| + \sin^2(\eta/2)\,|E_V|^2 \tag{6}$$

where η represents the relative phase retardance introduced by the birefringent material along the fast and slow axes. We can then reconstruct the phase $\Delta\phi(\lambda)$ using

$$\Delta\phi(\lambda) = \sin^{-1}\left(\frac{|E_H'(\lambda)|^2 - \cos^2(\eta(\lambda)/2)\,|E_H(\lambda)|^2 - \sin^2\left(\frac{\eta(\lambda)}{2}\right)|E_V(\lambda)|^2}{-\sin(\eta(\lambda))\,|E_H(\lambda)||E_V(\lambda)|}\right) \tag{7}$$

3. RESULTS AND DISCUSSIONS

Based on the above algorithm, we investigated the feasibility of the device by examining the performance of DLP reconstruction as a function of the photodetector's Degree of Asymmetry (DoA) defined as $\frac{R_{\parallel}(\lambda)-R_{\perp}(\lambda)}{R_{\parallel}(\lambda)+R_{\perp}(\lambda)}$. Figure 2(a) shows the DoA of an elliptically-shaped nanopillar LED with the ellipse's aspect ratio fixed at 3 as a function of temperature using an empirical model in [4]. It is observed that smaller nanopillars have a higher DoA. Figure 2(b) shows the accuracy of DLP's reconstruction as a function of the DOA. Here, a responsivity of 10^{-6} A/W is assumed. With a 1pA measurement accuracy, the DLP's reconstruction accuracy is around 95% or better with a 5% DOA, achievable with a nanopillar dimension smaller than 200 nm.

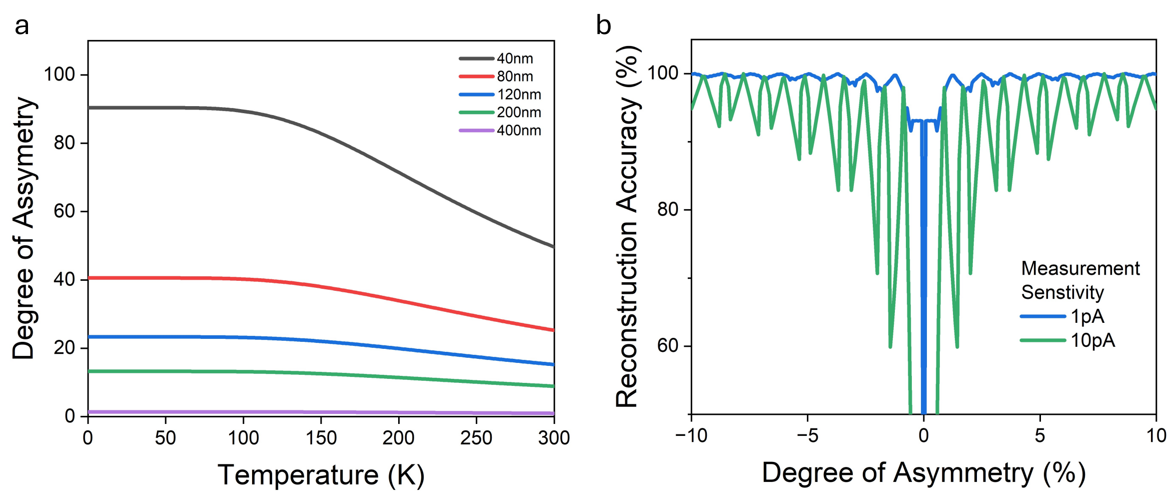

Figure 2 (a) Calculated Degree of Asymmetry (DoA) of elliptically-shaped nanopillar LEDs as a function of temperature. The aspect ratio of the ellipse used in this calculation is fixed at 3. The legend shows the minor axis diameter. (b) The reconstruction accuracy of DLP with photocurrent measurement sensitivity is set at 1pA and 10pA, respectively. The dark current is 1pA. A responsivity of 10^{-6} A/W is assumed.

In summary, an on-chip spectropolarimeter is proposed based on gallium nitride polarization and spectral encoders. The device consists of an array of GaN photodetectors. The building block for these detectors is a nanopillar-shaped GaN LED. The spectral responsivity is found to be sensitive to the optical signal's polarization. A pair of photodetectors with their respective building block's ellipse's major axes orthogonal to each other function as polarization encoders that can replace the linear polarizers in a conventional spectropolarimeter. Our analysis suggests that the two photodetectors' degree of asymmetry only needs to be 5% to deliver a 95% or better DLP reconstruction accuracy, a metric readily achievable with an elliptically-shaped nanopillar LED with a minor axis dimension less than 200 nm.

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REFERENCES

[1] J. Bao, M. G. Bawendi, "A Colloidal Quantum Dot Spectrometer," Nature 523 (2015) 67.

[2] T. Sarwar, C. Yara, X. Li, Q. Qu, and P.C. Ku, "Miniaturizing a Chip-Scale Spectrometer Using Local Strain Engineering and Total-Variation Regularized Reconstruction," Nano Lett., 22 (2022) 8174.

[3] P. Li, C. Yara, T. Sarwar, P.C. Ku, and Q. Qu, "Accelerating Deep Learning in Reconstructive Spectroscopy Using Synthetic Data,"Conference on Lasers and Electro-Optics, San Jose, CA (2023).

[4] C. H. Teng, L. Zhang, T. Hill, B. Demory, H. Deng, and P.C. Ku, "Elliptical quantum dots as on-demand single photons sources with deterministic polarization states," Applied Physics Letters, 107 (2015), 191105.

[5] J. Sui, P.C. Ku, "An Empirical Model for GaN Light Emitters with Dot-in-Wire Polar Nanostructures," Micromachines (2020), 11, 82.