Polarized Detection Using Patterned Polarizer Coated Quantum-Dot Detector

Debjyoti Bhadra*, Yuechu Cheng*, Vigneshwaran Swaminathan*, Jianxin Song*, Kumar Mallem*, Zebing Liao*, Yiyang Gao, Maksym F. Prodanov*, Olena Vaschenko*, Valeri V. Vashchenko*, Hoi-Sing Kwok,* Abhishek K. Srivastava*[1]

***State Key Laboratory on Advanced Displays and Optoelectronics Technologies and Centre for Display Research, Department of Electronics and Computer Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong 999077, China**
[1]IAS Center for Quantum Technologies,
The Hong Kong University of Science and Technology, Hong Kong, China

Abstract

The polarization state can encode far more information compared to the intensity and spectrum of light signals. Polarization imaging and determination of polarization state has been a fascination of researchers in the field of optical engineering. Conventional polarization imaging involves complex methods and expensive manufacturing processes. Additionally, in recent times easily fabricate able semiconductor devices such as solution processed quantum dot (QD) LEDs [16], quantum rod (QR) LEDs [13-15], QD photodetectors (PDs), etc. have gained tremendous interest and research efforts. The ability to fabricate a solution processable polarization detector can prove to be pivotal in the pursuit of facile polarization detection. Traditional polarization imaging systems make use of expensive wire-grid polarizers and complicated patterning processes that make it challenging to realize such devices, the resulting devices are also quite expensive which limits their widespread application. In this work we present a novel system that makes use of a completely solution process fabricated QD PD using lead sulfide (PbS) QDs that can detect the whole visible spectrum and integrate a solution processable Azo-dye polarizer (AD1) onto it to achieve patterned polarized detection. The PD achieved a response time of around 30 μs and the AD1 polarizer achieved a maximum extinction ratio of ~27:1. The fabricated AD1 polarizer also covers wavelengths in the range of 450 nm to 750 nm making it ideal for the visible spectrum. The work represents a significant step forward in a facile and cheap polarized detector fabrication method that can enable a wider adoption of polarization imaging. Further optimization in pixelization and device architecture is expected to lead to a widespread implementation of such technology.

Author Keywords

QD photodetectors; Polarization imaging; Broadband coat able polarizer; AD1

Introduction

Nanomaterials have attracted substantial attention in recent times due to their size-tunable emission peaks, low-cost synthesis methods, high photoluminescence quantum yield (PLQY), narrow full width at half maximum (FWHM) and relative ease in fabricating devices. [1] Additionally, their strong confinement leads to strong light-matter interactions in colloidal QDs (CQDs) making them ideal for active optoelectronic applications. [2] Extensive work regarding QD PDs has focused on device layer optimization and QD ligand modification for improved electronic performance leading to responsivities up to 444 A/W [3] and rise/decay times as small as 5.3/4.9 μs [4]. Moreover, the limitation in silicon's working wavelength range has piqued interest in lead sulphide (PbS) CQDs for their tunable band gaps between 0.6 and 1.6 eVs [2]. Importantly, solution processable PbS CQDs enable the potential utilization of unique flexible and curved substrates.

The polarization state of light contains an exceedingly high density of information compared to the wavelength or intensity of light. Detecting and decoding of this polarization state information can allow determination of material properties, surface characteristics, environment monitoring, stress analysis, [5] biological applications,[6] and even quantum information. Traditional polarization detection requires multiple components including polarizers, analyzers, and quarter waveplates. [19] Therefore, to minimize complexity of polarization detectors and to create a fully integrated detection system various methods such as meta surfaces. [7-9] However, the complex fabrication and optimization of such systems have proven to be hurdles in such technologies.

In this study we look to fabricate a fully integrated device that can image the polarization state of linearly polarized light. We demonstrate a completely solution processed device that includes a solution processed CQD PD with response times of around 30 μs and a broadband patternable and solution process able thin film polarizer. This device was then used to detect the polarization state of broadband white light with rotating input polarization state.

Device Fabrication

(i) QD photodiode (PD) fabrication

An all-solution process was used to fabricate the QD PDs according to Ref. [10] . Briefly, O_2 plasma cleaned substrates of ITO were coated with a layer of ZnO, 30 mg/ml in ethyl alcohol, as the electron extraction layer. The sample was then baked at 150 °C for 20 mins. Then, PbS QDs with an emission peak at 1550 nm, 50 mg/ml in octane at a concentration of 50 mg/ml was coated layer-by-layer deposition altering with a ligands modification in the each layer using either 10 mg/ml tetrabutyl ammonium iodide (TBAI) in methanol, for n-type behaviour, or 0.01 vol% of ethane dithiol (EDT) in acetonitrile, for p-type behaviour: an appropriate ligand exchange solution is coated onto a PbS layer and allowed to sit for 30 s before being spun for 10 s to remove the solution. The film was then washed twice with acetonitrile before repeating the process. This process was repeated 12 times, the first 6 times the ligand modification was done with TBAI and the final 6 layers were processed with EDT. The device was then baked at 100 ^{O}C for 10 mins. Aluminum (100 nm) of was evaporated as the cathode and the completed device was encapsulated with UV curable epoxy resin.[10]

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(ii) AD1 coat able polarizer fabrication

The thin film polarizer was fabricated by an all-solution process. The Azo-dye AD1 was dissolved in toluene at a concentration of 5 wt% and then spin coated at 1000 rpm for 30 s to obtain a uniform layer. The film was then aligned using a 436 nm light and multiple exposures were done for patterning the film. After patterning the film, the nature of the AD1 film was modified by protonation to increase the absorption and working range of the polarizer. [11]

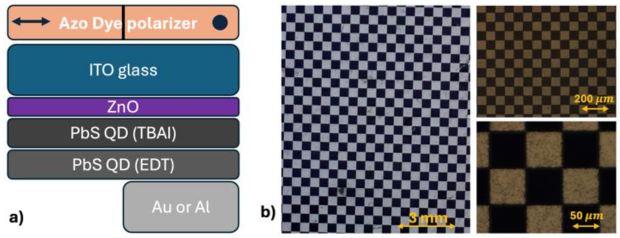

Figure 1: (a) Schematic of device structure, (b) Modified AD1-H thin film polarizer with 0.5 mm and 80 μm grid.

Results and discussion

The schematics for device fabrication are provided in Figures 2 and 3. The QD PD was fabricated with 12 layers of absorptive material and the AD1 thin-film polarizer was fabricated as described. The average thickness of AD1 film formed was around 150 nm.

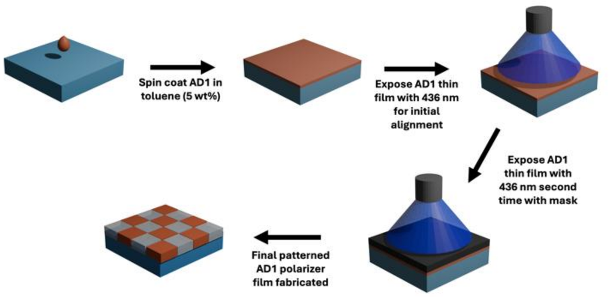

Figure 2: Schematic of AD1 thin-film polarizer fabrication.

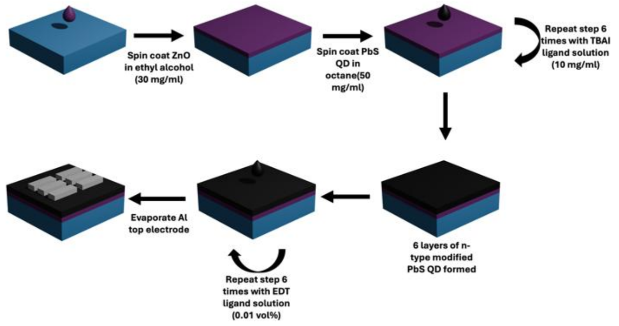

Figure 3: Schematic of CQD PD fabrication.

The absorption characteristics of the AD1 film was characterized before and after the modification process. A protonation process was conducted to modify the molecular properties of the AD1 film. This enabled the working range of the AD1 to increase from around 400 nm-550 nm to 400 nm-700 nm. [12] This enables our device to function over the whole visible spectrum. This modification of the AD1 film was conducted after patterning the AD1 to contain regions of patterned polarizer oriented at 0^{O}, 45^{O}, and 90^{O}.

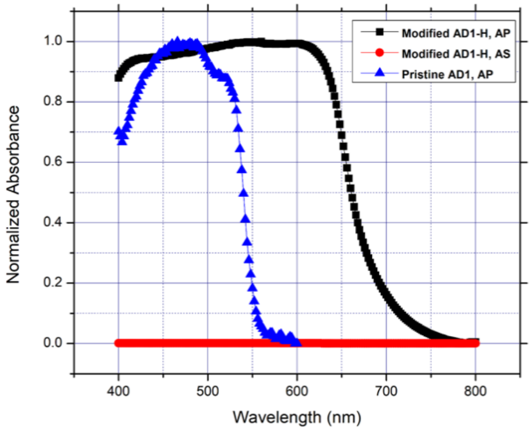

Figure 4: Absorption of AD1 and modified AD1-H.

The response of the PbS CQD PD is presented in Figure 5 showing the response from the device being driven by 633 nm laser input signal that was switched with a ferroelectric liquid crystal (FLC) shutter switching at 8 KHz frequency. The PD exhibited an ultrafast response speed with rise time, $\tau_{10\text{-}90}$ of around 30 μs and high responsivity of around 1 A/W.

$$R = \frac{I}{P}$$

R is the responsivity, I is the output current from the detector, and P is the power of the input light signal.

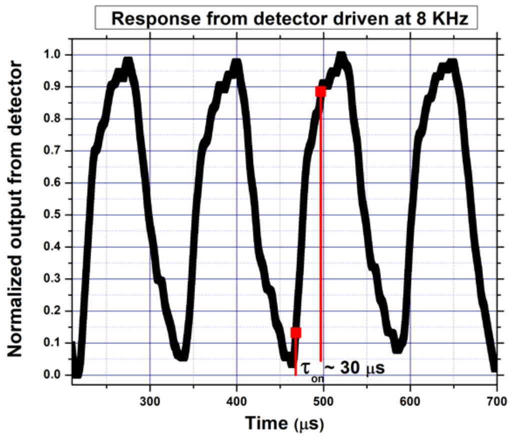

Figure 5: CQD detector response to 8 KHz input signal.

The integrated system for polarized detection was created by stacking the fabricated CQD PD with a separate glass substrate that was coated with the AD1 thin-film polarizer patterned to match the pixels of our PD, further developments can allow for PDs with AD1 patterned on top of the substrate to minimize losses. As for the input signal a white light source with random polarization state was used. A rotatable linear polarizer was then placed between the light source and the fabricated detector attached to the AD1 thin-film polarizer. As the input polarizer was rotated the response from the different pixels with AD1 polarizer oriented at different directions, 0^{O}, 45^{O}, or 90^{O}, changed providing us with three separate plots following Malus' law.

$$I(\theta) = I_0 cos^2(\theta)$$

θ is the angle of the rotatable polarizer, $I(\theta)$ is the output intensity at different rotatable polarizer angles, and I_0 is the initial intensity

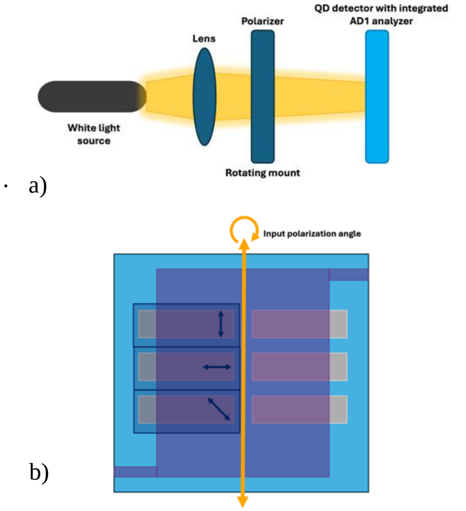

Figure 6: (a) Measurement setup for polarized detection, (b) Input polarization direction with respect to AD1 analyzer direction over the three pixels.

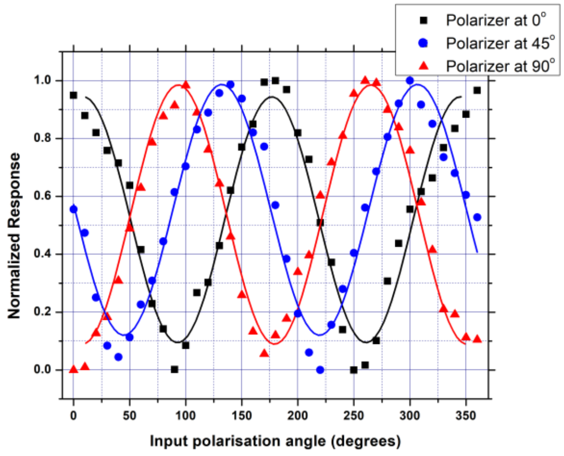

Figure 7: Output from detector with patterned AD1 thin-film polarizer.

4. Conclusion

In summary, in this work we present a facile fabrication method for an ultrafast and polarization sensitive detector with every component of the system being solution processable. The QD detector fabricated can achieve rise times as small as 30 μs and responsivities of up to 1 A/W at 0 V bias, in comparison to around 200 μs rise/decay time and 79 mA/W responsivity in a previously reported work. [20] Additionally, the thin film polarizer implemented in the system can operate over a broadband 400 nm-700nm and can cover the whole visible spectrum. The system constructed in this study has the potential of widespread application in polarization imaging systems in both visible and NIR regions. This enables a low-cost fabrication scheme that circumvents complicated and expensive meta surfaces and patterned wire grid polarizers.

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