Characterization of Electrical Crosstalk in PbS Quantum Dot CMOS Image Sensors for Ultra-High-Resolution Imaging

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Abstract

The electrical crosstalk of QD-based CMOS image sensors is studied in this work. We modified existing crosstalk models to suit QD-CIS systems and designed specialized electrode patterns to analyze electrical crosstalk in multi-pixel QD photodiode devices, refining predictions and improving sensor architecture for high- quality imaging applications.

1. Introduction

CMOS (Complementary Metal Oxide Semiconductor) image sensors have undergone a transformation from being considered to have poor performance to being widely used in the field of optoelectronic imaging since their 1970s US origin. Originally, due to its larger size and performance comparison with CCD (charge-coupled device) and not widely adopted, but with the rapid development of large-scale integrated circuit technology in the 1990s, CMOS image sensor defects have been significantly improved. Nowadays, they are not only used in civilian fields such as video cameras and security surveillance cameras, but also play a key role in military fields such as guidance, identification and reconnaissance.

Meanwhile, lead sulfide (PbS) quantum dots, as a narrow-band semiconductor material, has become an important material in the research of colloidal quantum dots due to its significant quantum effect at room temperature and large exciton Bohr radius (20 nm) and Debye length (88 nm). These unique properties of PbS quantum dots have led to breakthroughs in applications such as infrared photodetectors, photovoltaic solar cells, light-emitting diodes and chemical sensors[1].

In this work, we focus on enhancing CMOS image sensors (CIS) with PbS quantum dots to improve infrared sensitivity and overall performance. We modified existing crosstalk models to account for the unique properties of QD-CIS systems, incorporating the effects of PbS quantum dots' exciton dynamics and carrier diffusion. Additionally, we designed and fabricated a novel electrode pattern to analyze electrical crosstalk in multi-pixel QD photodiode devices, enabling precise measurement of crosstalk between adjacent pixels. This research aims to refine crosstalk predictions and improve sensor architecture for high-quality imaging in various applications.

2. Experiment Section

2.1. QD CIS Architecture

Combining the proven technology of CMOS image sensors with the excellent optoelectronic properties of PbS quantum dots, researchers can develop advanced optoelectronic detection and imaging devices with high sensitivity and broad spectral response[2]. As is shown in **Figure 1.**

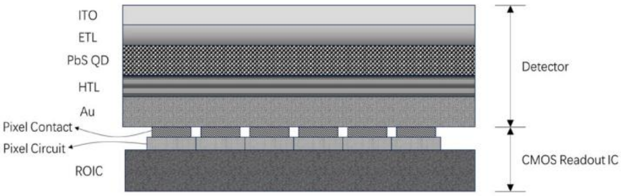

Figure 1. The integration of PbS QD photodetectors with CMOS ROIC

The integration of PbS quantum dots not only enhances the infrared sensitivity of CMOS image sensors to detect infrared light, which is normally invisible to conventional CMOS sensors, but also provides a significant advantage to imaging devices through its high absorbance and broad spectral responsivity, providing higher resolution and photoelectric conversion efficiency for imaging sensors. In addition, the relatively simple and low-cost synthesis of PbS quantum dots helps reduce the overall cost of high-performance imaging systems, while their compatibility with conventional silicon-based CMOS processes facilitates the rapid development and deployment of new high-performance image sensors. This combination of technologies provides more accurate and efficient solutions in areas such as photography, video surveillance, biomedical imaging and remote sensing.

2.2. Electrical Crosstalk

In CMOS image sensors, signal amplifiers and analog-to-digital converters are integrated into each photoreceptor, requiring only a single operating power source. This integrated design allows for real-time reading of electrical signals while capturing optical signals, simplifying the signal reading process, while also enabling real-time processing of image information at each pixel. However, in practice, it has been found that a certain degree of crosstalk exists between pixels in the incident light irradiation range. The so-called inter-pixel crosstalk refers to the phenomenon that neighboring pixels interact and interfere with each other, i.e., the response of a pixel is not only affected by its incident light, but also by other pixels around it. This crosstalk phenomenon may negatively affect the image quality. Therefore, the crosstalk problem in CMOS image sensors has been of great concern.

Electrical crosstalk is one of the difficult problems of CMOS image sensors, and certain crosstalk signals are also generated in the normal operating range. Electrical crosstalk in CMOS image sensors is when the non- equilibrium carriers generated by incident light into the photoreceptor area have a certain chance of lateral diffusion into the adjacent pixel area and are collected by the neighboring area before diffusing into the depletion area to be collected, as is shown in **Figure 2.**

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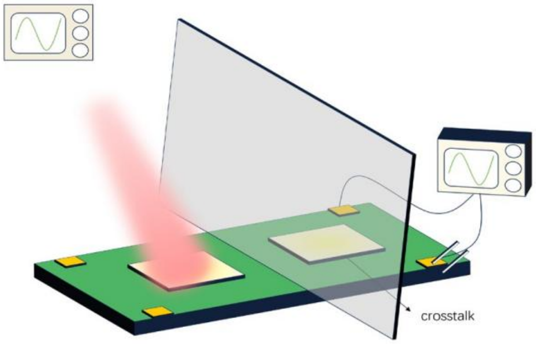

Figure 2. Schematic diagram of electrical crosstalk in QD CMOS image sensors.

2.3. Substrate Preparation

2.3.1. Focused Ion Beam Cutting

Using a focused ion beam-electron beam dual beam electron microscope-time-of-flight secondary ion mass spectrometry cascade system(Helio5UX), the separation of individual pixel points was carried out by the focused ion cutting technique, and the Si-on-Au substrate was ionized at the pixel junctions so that each pixel point was independent. As shown in **Figure 3** below.

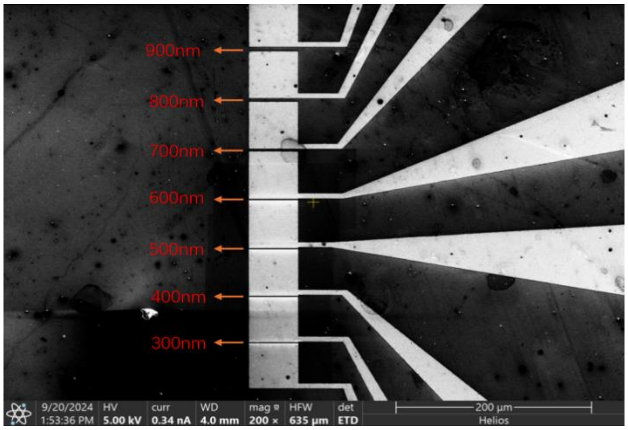

Figure 3. Individual pixes with different pixel pitches

The apparatus for performing focused ion beam cutting is shown in **Figure 4.**

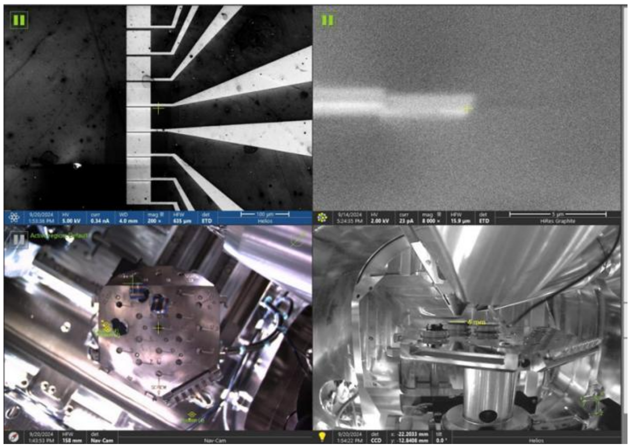

Figure 4. Helio5UX global image

The cut Si-on-Au substrate is shown in **Figure 5.**

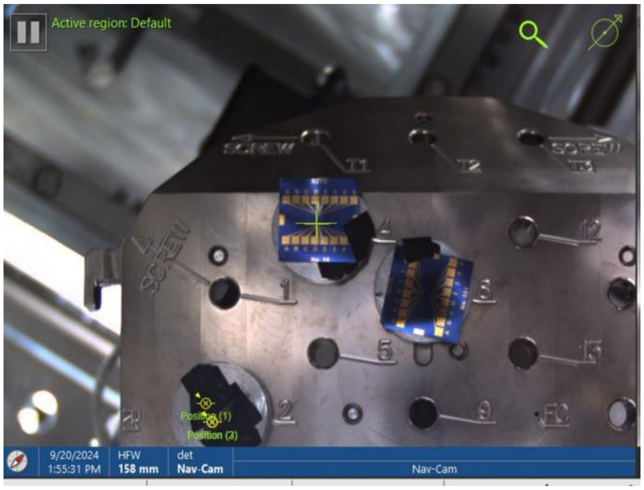

Figure 5. Si-on-Au substrates

2.4. Experimental Procedure

2.4.1. Introduction to photodiode device structure

Photodiode-type devices usually use different materials to prepare N-type layers to form heterojunctions with PbS, however, different materials require different processes to realize. A heterogeneous PIN junction photodetector based on PbS colloidal quantum dots has been prepared by a spin-coating process. The process is highly reliable and maneuverable, which is very favorable for the application of PbS quantum dot devices in face array chips.

In this study, we constructed photodiodes using Si-on-Au substrates. Previously, we have successfully realized the fabrication of photodiodes on ITO/ZnO/PbS QDs/EDT/(MoO_3/Ag) structures, demonstrating excellent performance. Based on this achievement, we have mastered the fabrication of photodiodes using ITO as the bottom electrode. We will introduce this device in more detail below.The device structure is shown in **Figure 6.**

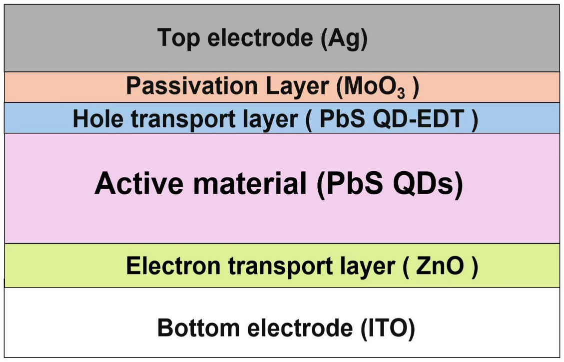

Figure 6. Device Structure Diagram

The device in this study utilizes a composite PIN structure employing Ag as the top contact layer, i.e., the top electrode. Molybdenum disulfide (MoO_3) was used as the hole transport layer, and PbS quantum dots were employed as the photoactive layer responsible for absorbing the incident light and generating electron-hole pairs. PbS quantum dots are particularly suitable for infrared light detection due to their tunable bandgap and high light absorption coefficient. Zinc oxide (ZnO) is used as the electron transport layer. The following is a diagram of its device structure.

2.4.2. Photodiode device characterization

The photoelectric performance of the prepared detector has been tested and analyzed, and the results show that the response of the device is linear under different incident light intensities, and the response and specific detectivity of the device are good at specific wavelengths under -0.5 V bias, which demonstrates the excellent ability of the device in detecting the weak incident light. This is a characterization diagram of the photodiode.

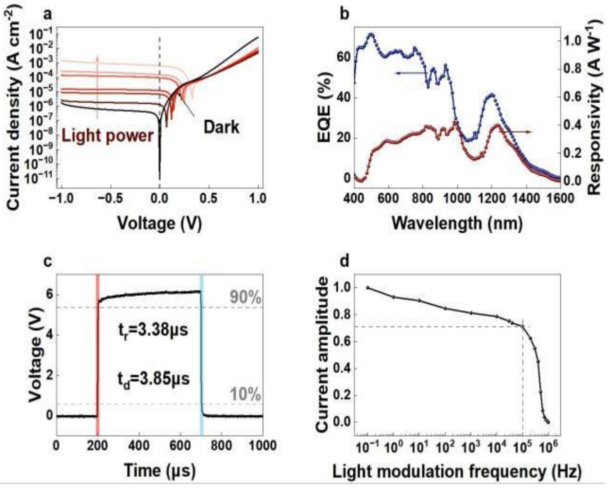

Figure 7. Device characterization chart

3. Results and Discussion

3.1. Theoretical Modeling of Crosstalk

The electrical crosstalk of traditional CIS has been studied in previous work[3]. The electrical crosstalk signal between the pixel cells have analyzed as is shown in **equation 1**:

$$V_{\mathrm{diff}}(\lambda)/N_{P\lambda}=C_g\times k(c_1A+c_2Pd)(\frac{S-A}{S})\ (1\text{-}8L_{\mathrm{diff}}4P_i\text{-}P)\ (1)$$

where C_g is the conversion gain of electrons converted to voltage; k is the number of electrons diffused into the sidewall of the photodiode per unit area in the total number of electrons collected by the sensor; A is the area of the photodiode sensing area; P is the perimeter of the photodiode sensing area; d is the width of the photodiode depletion layer; S is the area of pixel cells; Pi is the size of the pixel cell; L_{diff} is the diffusion length of electrons within the substrate; coefficients c_1 and c_2 denote the amount of generated carriers diffusing into the photodiode depletion region of the neighboring pixel cell through the bottom and side edges, respectively. $V_{\mathrm{diff}}(\lambda)$is the electrical crosstalk signal between the pixel cell and the neighboring pixel cell and $N_{P\lambda}$is the number of incident photons.

3.2. Electrode for Crosstalk Analyze

To analyze the electrical crosstalk of the QD CIS, we designed and fabricated an electrode substrate based on patterned gold as bottom contact for pixels, as is shown in Figure 3. The separation between each contact is set from 100 nm to 5 µm, respectively. Patterns with separation above 3 µm are fabricated using a standard contact lithography. Those patterns with separation under 3 µm are fabricated using a maskless laser lithography system with process precision about 10 nm.

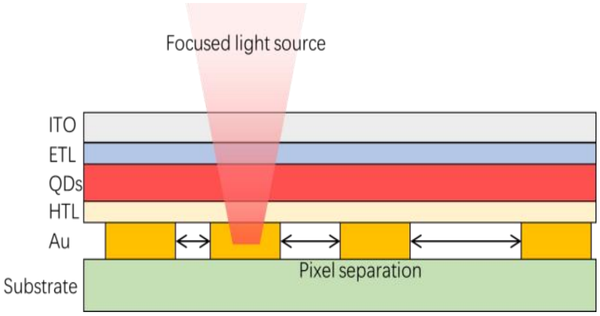

Figure 8. Schematic diagram of electrode designed for crosstalk analyze. The pixel separation is set as 100 nm,200 nm,500 nm, 1µm, 2µm, 5µm.

3.3. Numerical simulation results and analysis

In the design of CMOS image sensors, the overall electron crosstalk is closely related to the area of the pixel cell and the diffusion length of carriers within the device. The intensity of electron crosstalk can be effectively regulated by adjusting the pixel pitch to change the pixel cell area and by selecting different materials to adjust their mobility to affect the diffusion length of the electrons. In this study, PbS quantum dot material is used, whose mobility is generally in the range of 10^3 to 10^4 cm²/(Vs). Meanwhile, we set the pixel sizes including 100 nm, 200nm, 500nm, 1µm, 2µm, and 5µm, based on which we performed quantitative analysis to investigate the effects of pixel spacing and material mobility on the electrical crosstalk.

3.3.1. Effect of pixel pitch on electrical crosstalk

The conversion gain was set to 0.32µV/e, T=300K, the pixel cell size was 30µm x 30µm, the diode external quantum efficiency was 80%, the dark current density was 100nA/cm2, the incident optical power was 50µA/cm2, the Quantum Dot was 4nm, the carrier lifetime was 2.5ns, the absorption coefficient was 104, and the mobility was 0.01, the pixel spacing was set as the independent variable and the images were normalized.The variation of electrical crosstalk with pixel spacing is shown in **Figure 9.**:

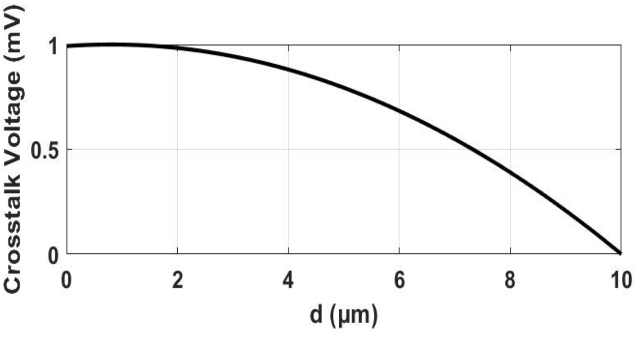

Figure 9. Electrical crosstalk versus pixel pitch curve

Roughly speaking, it can be seen that the electrical crosstalk intensity decreases with increasing pixel spacing, provided that the other variables are controlled to be constant and the pixel spacing is controlled to be in a specific range.

3.3.2. Effect of mobility on electrical crosstalk

The diffusion length of electrons is an important parameter affecting the electrical crosstalk, and the change of mobility can directly affect the diffusion length of electrons **equation 2 and**

3:

$$L = \sqrt{D\tau} \qquad (2)$$

$$D = \mu kT/q \qquad (3)$$

when $\tau=2.5$ns, $k=1.380649\times10^{-23}$J/K, $q=1.602176634\times10^{-19}$Coulombs , T = 300K, the relationship between mobility and diffusion length can be calculated. The material mobility was set as the independent variable and the images were normalized. The variation of electrical crosstalk with mobility is shown in **Figure 10.**

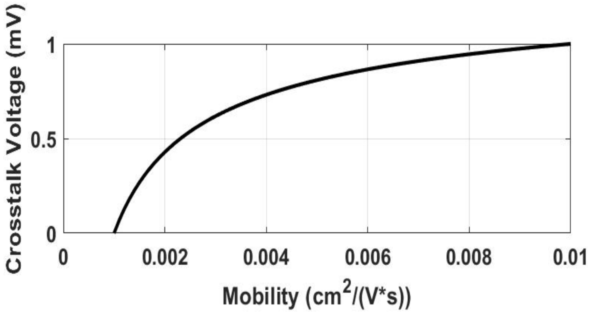

Figure 10. Electrical crosstalk versus mobility curve

Roughly speaking, it can be seen that the electrical crosstalk strength increases with increasing material mobility, provided that the other variables are controlled to be constant and the mobility is controlled to be in a specific range.

4. Conclusions

In conclusion, we successfully modified existing crosstalk models for conventional CMOS image sensors to accommodate the unique properties of QD-CIS. This adaptation accounted for the exciton dynamics and carrier diffusion specific to PbS quantum dots, enabling more accurate predictions of crosstalk effects. Additionally, we designed and fabricated a novel electrode pattern to analyze electrical crosstalk in multi- pixel QD photodiode devices. This design facilitated precise measurement and characterization of crosstalk between adjacent pixels, providing valuable insights to refine sensor architecture. Our work paves the way for the development of high-performance QD-CIS with improved infrared sensitivity and image quality.

5. References

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