

博士論文 (要約)

Highly sensitive organic image sensor with diode-stacked pixels

(ダイオード積層構造を用いた高感度有機イメージセンサ)

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Abstract

Organic image sensor is an emergent type of image sensor that utilizes organic materials in the light-sensitive layers or devices. The excellent absorption and sensitivity, low temperature and large area process compatibility, and their mechanism flexibility has made the organic image sensors promising for novel imaging applications, especially in medical and wearable imaging applications.

Among the organic image sensors, the ones with the pixel structure of diode stacks has been of great interest. This image sensor integrated the organic photodetectors and switching components in a single stack, which has a simple, vertically stacked, and two-terminal structure. The fabrication of this image sensor became simplified, which does not require additional electronic components in pixels. With this, high-resolution organic image sensors could be achieved.

However, the organic image sensors with diode-stacked pixel still leaves rooms for improvement. First, this image sensor required higher static power because individual pixel was not able to turn off at 0 V. Second, this image sensor showed a limited photo-responsivity due to the simplicity of the architecture with the fundamental limit of the organic photodiode.

In this dissertation, we aim to enhance the sensitivity of the organic image sensor with diode-stacked pixels. The outline of the dissertation is listed as below.

Chapter 1 Introduction

The topic of the dissertation, which is the organic image sensor with diode-stacked pixels, was introduced. Then the issue regarding this topic that will be discussed in this dissertation was mentioned.

Chapter 2 Organic image sensor

The fundamentals and background knowledge of organic image sensor was introduced. Firstly, the motivations of developing organic image sensor was mentioned. Then, organic photodetectors, the most essential components in the organic image sensor, were introduced. It is followed by the introduction of different types of organic image sensors to date. This chapter ends with the discussion of the applications of the organic image sensors.

Chapter 3 Materials and methods

The experimental materials and methods were introduced. This includes the materials, fabrication methods, and characterization methods utilized in the studies of the organic image sensor in this dissertation.

Chapter 4 Low-power organic image sensor based on diode-stacked pixels by turn-on voltage modification

The first work of this dissertation is summarized in this chapter. The organic image sensors with diode-stacked pixel still required higher static power because individual pixel was not able to turn off at 0 V. Here, we demonstrated low standby power organic image sensor based on two-terminal pixels. Our organic image sensor exhibited improved imaging on/off ratio while achieving zero static turn-off power consumption.

Chapter 5 Highly responsive organic image sensor based on diode-stacked pixels with photomultiplication

The second work of this dissertation is summarized in this chapter. The organic image sensor with diode-stacked pixels still showed a limited photo-responsivity due to the simplicity of the architecture with the fundamental limit of the organic photodiode. Here, we achieved a simple diode-stacked organic image sensor with high responsivity. Our photodetector pixel has a high responsivity, a low dark current, and a high on/off ratio. With this, the diode-stacked organic image sensor has a high current response with a low light imaging capability.

Chapter 6 Summary and prospect

Finally, we concluded the dissertation. We have demonstrated both low-power and highly responsive organic image sensor with diode-stacked pixels in this dissertation. With these achievements, the future work and the prospect of the work were delivered.

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1 Introduction

1.1 Organic image sensor

Organic image sensor is an emergent type of image sensor that utilizes organic materials for the light-sensitive layers or devices¹. In an organic image sensor, the organic photodetector is the most crucial component, which is responsible for the light sensing²⁻⁴. Organic image sensor is a two-dimensional and multiplexable matrix of organic photodetectors¹.

1.2 Organic image sensor based on diode-stacked pixels

Organic image sensor based on diode-stacked pixels is simple in terms of architecture and manufacturing.⁵ This type of organic image sensor consisted of a monolithically processed rectifying pixels of organic photodetectors. The two-terminal pixel architecture is the simplest possible structure.

1.3 Objective of this study

Despite the simple architecture, facile fabrication, and the novel imaging applications of this organic image sensor with diode-stacked pixels, there are several bottlenecks that need to be solved. First, the individual pixel could not be switched off at 0 V. This led to a non-zero turn-off voltage, which resulted to a higher standby power. Secondly, the responsivity of this organic image sensor was limited. This organic image sensor utilized organic photodiode as its photodetector component.

1.4 Outline of this dissertation

The current chapter serves as the introduction of the dissertation to introduce the brief background knowledge, motivation, and objective of the study.

In Chapter 2, the background knowledge, including the mechanism, physics, and previous studies of both organic photodetectors and organic image sensors are introduced and summarized.

In Chapter 3, the experimental materials and method in the study, including the materials, fabrication, equipment, characterization, and analysis for the organic image sensor, are introduced.

In Chapter 4, a comprehensive study of the low-power organic image sensor based on two-terminal pixels is demonstrated.

In Chapter 5, a thorough investigation of the organic image sensor based on two-terminal pixel with high responsivity is presented.

In Chapter 6, the summary of this dissertation is given. Future outlook of this research is also presented.

2 Organic image sensor

This chapter is intended to provide the background knowledge and review of up-to-date studies regarding the organic image sensors.

2.1 Introduction of organic image sensor

2.1.1 Motivation of developing organic image sensor

Image sensors is an indispensable component in the consumer electronics that are utilized in our daily needs for imaging, such as digital cameras and cameras in mobile phones. Recently, the needs of novel imaging applications have fostered the emergent types of image sensors that have unconventional and unprecedented properties. To achieve that, an image sensor needs to be flexible, deformable, and conformable onto the skin. Image sensors made of organic materials are promising for these novel applications.

2.1.2 Definition of organic image sensor

Organic image sensor is an image sensor made of organic light-sensitive devices.⁶ It is a complex system, which is more than a single organic photodetector component. Commonly, an organic image sensor is a two-dimensional, multiplexable matrix with individually addressable pixels of organic photodetectors¹.

2.2 Organic photodetector

2.2.1 Introduction to organic photodetectors

Organic photodetector is the most essential component in an organic image sensor. It is a photodetector made of organic light-sensitive materials. Photodetectors are sensors of light or other electromagnetic radiation. It converts the radiation of light into electric signal, either in the form of current or voltage.

2.2.2 Figure of merits of organic photodetector

There are several figures of merits for the evaluation of the performance of photodetectors. Important figures of merits including responsivity, detectivity, dynamic range, and response speed.

2.2.3 Organic semiconductors

Organic photodetectors utilize organic semiconductor materials as the active materials and layers.^{2,3} Organic semiconductors consist of individual organic molecules or polymers.⁷

2.2.4 Organic photodiode

Organic photodiode is a vertically stacked and two-terminal photodetector with organic light-sensitive layers.^{2,3} At least one of these two electrodes is transparent to allow the light to enter the organic photoactive layer. The photoactive layer is sandwiched between the two electrodes and absorb light with the wavelength of interest.

2.3 Organic image sensor with organic photodiodes and passive addressability

This section discusses several common approaches to integrate organic photodiode with electrical switches to achieve multiplexing in the organic image sensor. Transistors are the most common electrical switching element for the multiplexing in a sensor matrix or display. A sensor element is connected in series with the source/drain of the transistor. Switching of the sensor is then controlled by manipulating the gate voltage of the transistor. In a transistor, the current flow in between the source and drain is controlled by the gate voltage. Different “turn-on” and “turn-off” gate voltages could modulate the on/off state of the transistor. Therefore, in conjunction with the sensor element, the electric signal from the sensor could also be switched on/off with the suitable gate voltages of the transistor.

2.4 Organic image sensor with intra-pixel amplifications

An organic image sensor needs high output current to achieve high sensitivity and responsivity. It can be achieved by several methods, including using intra-pixel amplifiers. The intra-pixel amplification of organic image sensor pixel could be achieved by integrating organic photodiode and switching transistors with amplifying components altogether in a single pixel.

2.5 Applications of organic image sensor

Organic image sensor has novel properties such as tunable light sensitive wavelength using different organic semiconductors, as well as large-area, low-temperature fabrication on flexible substrates. This leads to novel applications such as non-visible light imaging and large-area, flexible image sensors for wearable and biomedical imaging applications.

3 Materials and methods

This chapter introduces the materials and experimental methods that have been utilized for the study in the dissertation. This includes the materials that are used for the organic image sensors, the fabrication methods of the organic image sensors, and the characterization methods of the organic image sensors.

3.1 Materials

The most important part of the organic photodetector that gives the photosensitivity is the organic semiconductor materials. In an organic photodetector, electrode is as important as the active materials.

3.2 Device fabrication methods

Organic image sensors are formed by organic photodetectors and other components. These devices are formed by a stack of several layers, which consists of several thin films ranging from a few nanometers to a few hundreds of nanometers. Patterning the thin films are crucial to define the horizontal structure of the thin films. Encapsulation is crucial to protect the device from environmental degradation, such as the degradation by oxygen and humidity.

3.3 Characterization

The current-voltage characteristics is important of a semiconductor or optoelectronic device. It is important to know how the response of the photodetector react with different wavelength of light. The temporal or dynamic response of the organic photodetector is also important.

4 Low-power organic image sensor based on diode-stacked pixels by turn-on voltage modification

4.1 Introduction and objective of this study

Organic image sensor based on monolithically and vertically stacked, two-terminal organic photodiode-blocking diode pixel has the great advantage of an extremely simple pixel structure. However, they require higher static power because individual pixel could not be turned off at 0 V. In previous studies, the diode-stacked pixels required a non-zero voltage (+0.5 V) to turn off the pixel⁵. As wearable image sensors require low-power operation and reduced complexity of read-out circuitry, it is crucial to reduce the power of the organic image sensor by enabling the individual pixel to be switched off at 0 V, which is commonly referred as “normally off”.

In this chapter, we demonstrated low standby power organic image sensor based on diode-stacked pixels. With these, our organic image sensor exhibited improved imaging on/off ratio while achieving zero static turn-off power consumption.

4.2 Summary

We demonstrated low power organic image sensors based on diode-stacked pixels. We anticipate that these results could lead to low-power image sensors for wearable optical imaging applications.

5 Highly responsive organic image sensor based on diode-stacked pixels with photomultiplication

5.1 Introduction and objective of this study

Enhancing the pixelwise responsivity in the organic image sensor is always important for real-world applications such as medical imaging and wearable imaging applications. Enhancing the photocurrent means better sensitivity for sensing and imaging. Also, higher photocurrent could overcome the noise level limited by the readout circuit. Enhancing the responsivity was usually achieved by the integration of photodetectors with amplifiers^{8–10}, or the use of transistor-based organic photodetectors^{11,12}. By integration with (several) transistor-based devices, the layout of single pixel would become complicated, especially compared with the diode-stacked structure⁵. Therefore, it is important to have an organic image sensor with high responsivity while maintaining simple pixel structure.

However, there did not exist a solution that could achieve high pixelwise responsivity with a simple structure such as the diode-stacked structure. While the diode-stacked pixels organic image sensor has simple architecture, it does not allow enhancing the pixelwise response because the response is limited by the organic photodiode component. Organic photodiodes utilize the photovoltaic effect, which indicates that one photon generates one electron.² Thus, the electron-to-photon ratio is capped at 100%. Due to the simple structure, there is no room for inserting intra-pixel amplifier. Adding any intra-pixel amplifier would destroy the simple structure of the diode-stacked pixel structure.

In this chapter, we demonstrated a simple-structured diode-stacked organic image sensor with high responsivity (much higher than organic photodiode). Our photodetector pixel has a high responsivity, a low dark current, and a high on/off ratio. With this, the diode-stacked organic image sensor shows a high current response with a low light imaging capability at a light intensity level.

5.2 Summary

We demonstrate highly responsive organic image sensor based on monolithic, vertically stacked two-terminal pixels with organic photomultiplication photodetector. We foresee that

our organic image sensor establishes a foundation for realizing both highly sensitive and high-resolution flexible imaging.

6 Summary and prospect

6.1 Summary

In this dissertation, organic image sensors based on diode-stacked pixels have been realized. The single pixel of the organic image sensors consists of a vertical stacking of organic photodetectors with rectifying component. Furthermore, the sensitivity has been enhanced in two aspects. One is reducing the crosstalk at zero turn-off voltage for low static power driving. The second is increasing the responsivity of the organic photodetector.

6.2 Impact of this research

The impact of the research in this dissertation is listed as follows:

Impact on organic image sensor and applications:

1. Organic image sensor could be achieved with the simplest pixel architecture, which is suitable for simple fabrication and high resolution suitable for flexible sensor manufacturing.
2. Low-power organic image sensor with simple pixel architecture could be beneficial for wearable imaging system due to the lack of power source in wearable system.
3. Highly responsive organic image sensor could be achieved with an ultimately simple pixel architecture, without the need of intra-pixel amplifiers. This leads to highly sensitive imaging under weak illumination.

6.3 Future research and prospect

Several future directions and issue of research based on diode-stacked organic image sensor is suggested:

- Higher resolution.
- Flexible image sensor and flexibility.
- Stability.
- Reducing dark current of organic photodetector.
- Different sensing range of wavelength.
- Larger responsivity.

- Faster response time.
- Mechanism studies.

Here, organic image sensor with diode-stacked pixels that we have developed demonstrate the feasibility of highly sensitive imaging. When future investigations solve the remaining issues, the resulting widespread accessibility to organic image sensors will accelerate innovation in the fields of wearables and healthcare sensing.

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Publications related to this dissertation

JOURNAL PAPERS

1. **Yi-Lin Wu**, Naoji Matsuhisa, Peter Zalar, Kenjiro Fukuda, Tomoyuki Yokota, Takao Someya, Low-Power Monolithically Stacked Organic Photodiode-Blocking Diode Imager by Turn-On Voltage Engineering, *Advanced Electronic Materials* 4(11), 1800311 (2018).
2. **Yi-Lin Wu**, Kenjiro Fukuda, Tomoyuki Yokota, Takao Someya, Highly responsive organic image sensor based on two-terminal organic photodetector with photomultiplication, Submitted to *Advanced Materials* and under revision.

CONFERENCE PRESENTATIONS

1. **Yi-Lin Wu**, Naoji Matsuhisa, Peter Zalar, Kenjiro Fukuda, Tomoyuki Yokota, Takao Someya, Turn-on voltage engineering of monolithically-stacked organic photodiode-blocking diode toward low power organic imager, 2018 International Conference on Solid State Devices and Materials, Tokyo, Japan, Sep 2018 (Oral presentation)
2. **Yi-Lin Wu**, Peter Zalar, Naoji Matsuhisa, Mari Koizumi, Tomoyuki Yokota, Kenjiro Fukuda, Takao Someya, Turn-on voltage control of monolithically-integrated organic photodiode-diode photodetector toward normally-off organic image sensor with simplified readout, CEMSupra 2018, Tokyo, Jan. 9-10, 2018 (Poster presentation)

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