Material Selection and Performance Optimization of Deep Ultraviolet Photodetectors- A Comparative Study of Silicon-Based and Wide-Bandgap Semiconductors

Leyu Meng*

Science, University of Waterloo, Waterloo, N2L3G1, Canada

*Corresponding author: l4meng@uwaterloo.ca

Abstract. With the development of science and technology and the demand of advanced technology, deep ultraviolet photodetector has gradually become an important research direction in the field of optoelectronics. Deep ultraviolet photodetectors are widely used in the fields of environmental monitoring, biomedical imaging, military reconnaissance, and outer space environment detection. However, the current deep ultraviolet detection technology faces the challenge of low response speed, sensitivity, accuracy, and monitoring stability in complex environments. By comparing the photoelectric properties of silicon-based materials and wideband gap semiconductor materials, the effects of different materials on the performance of deep ultraviolet photodetectors are analyzed. It is pointed out that one of the keyways to optimize the performance of deep ultraviolet photodetectors is the selection of materials. Studies have shown that although silicon-based materials have the advantages of low cost and high integration, wide-band gap semiconductor materials such as gallium nitride perform better in terms of sensitivity, visible blind zone characteristics and environmental stability. This paper provides a valuable reference for the design of deep ultraviolet detectors in the future and points out the tradeoff and optimization direction of material selection.

Keywords: Deep UV detector, Wide band gap, silicon-based material, Material selection, optimization.

1. Introduction

With the development of science and technology and the demand for high precision technology, deep ultraviolet photodetector has gradually become an important research direction in the field of optoelectronics. Deep ultraviolet photodetector can effectively detect the short wavelength of ultraviolet light, which has a wide range of applications for environmental monitoring, biomedical imaging, military reconnaissance and outer space environment detection and other advanced fields [1]. However, the current deep ultraviolet photodetector technology faces some challenges, such as detector response speed, sensitivity, accuracy, and monitoring stability in a variety of complex environments. The key to these problems lies in the material selection of the deep ultraviolet photodetector, which is one of the key factors affecting the detector performance [2].

This paper will start with the principle and structure of the deep ultraviolet photodetector and analyze its advantages and disadvantages in practical application by comparing the photoelectric characteristics of different materials and the performance of the photodetector. For the comparison of silicon-based materials and wideband gap semiconductor materials, we will explore how to strike a balance between cost, integration, accuracy, and stability to optimize the performance of deep UV detectors. Through the research in this paper, we aim to provide a valuable reference for the material selection of deep ultraviolet detectors and point out the direction for future detector design.

2. Deep UV detector principle and material selection

2.1. Principle and structure analysis of deep UV photodetector

Deep ultraviolet photodetectors are based on the photoelectric effect. The photons of deep ultraviolet light have a relatively high energy, and when the deep ultraviolet light shines on the photosensitive material of the photodetector, such as a semiconductor material or a photoconductive material, these high energy photons interact with the electrons in the material, and the energy of the photons is absorbed by the electrons. The electrons in semiconductor materials are usually in the valence band and are in a lower energy state. When the energy of the photon is greater than or equal to the band gap energy of the semiconductor material, that is, the energy difference between the valence band and the conduction band, after the photon transfers the energy to the electron, the electron will obtain enough energy to overcome the energy difference between the valence band and the conduction band, and the electron will jump from the valence band to the conduction band [3]. This transition excites the electron from its normal position to a higher energy state and leaves an electron hole in the valence band. Thus, the excitation of a photon of deep ultraviolet light not only produces a free electron in the conduction band, but also leaves an electron hole in the valence band, and the combination of electron and electron hole is called an "electron-hole pair". In a deep ultraviolet photodetector, an applied electric field is usually applied, which exerts opposite forces on the electrons and holes, so that the electrons will be accelerated in one direction, and the holes will move in the opposite direction, so that the photocurrent will be generated [4]. If the photodetector is designed in voltage output mode, then the separation of electrons and holes will produce a photovoltage, photocurrent or photovoltage whose intensity is proportional to the intensity of the light, and can therefore be used to detect the intensity of the light signal.

The structure of deep ultraviolet photodetector mainly includes: light absorption layer, p-n junction structure, electrode, back electrode and substrate, passivation layer and protection layer. The optical absorption layer is the most important part of the deep ultraviolet photodetector, which determines the photoelectric conversion efficiency, responsiveness and spectral selectivity of the photodetector. The material used as a light-absorbing layer needs to have good absorption characteristics in the deep ultraviolet band and have a wide enough bandwidth to avoid the absorption of visible or near-ultraviolet light. Therefore, it is very important to choose the right material as the light absorption layer, which is also one of the important ways to improve the deep ultraviolet photodetector. The p-n junction structure in deep ultraviolet photodetector is the core structure, which directly affects the photoelectric conversion efficiency and response speed of the detector [5].The p-n junction is typically formed by combining P-type and N-type semiconductor materials, and an internal electric field is formed at the contact interface of the two types of semiconductors, which can effectively separate free electrons and electron holes and reduce the recombination of carriers, so as to improve the photoelectric response of the photodetector. The P-type semiconductor has more holes by adding acceptor impurities, and the N-type semiconductor has more electrons by adding donor impurities. Therefore, when a P-type semiconductor and an N-type semiconductor material contact to form a p-n junction, electrons diffuse from the N-type semiconductor to the P-type semiconductor, and holes transfer from the P-type semiconductor to the N-type semiconductor. In the contact region, electrons combine with holes to form the depletion region, where a built-in electric field is formed [6]. The p-n junction structure diagram: depletion region generated by diffusion of electrons and holes is shown in Fig.1 [7].

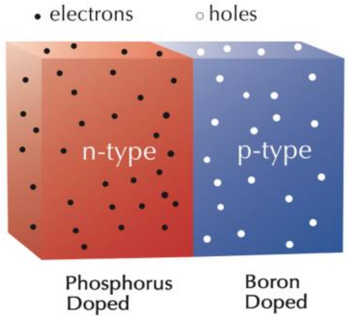


Fig.1 p-n junction structure diagram: n-type and p-type materials brought together [7].

2.2. Analysis of silicon based deep ultraviolet photodetectors

Silicon-based deep ultraviolet photodetectors have some advantages and limitations in the application of deep ultraviolet band. The use of silicon material as a light absorption layer material has some performance advantages, first of all, for the processing of silicon has a relatively mature technology, silicon-based photodetectors are widely used in the microelectronics industry, the technology is very mature, which makes the processing cost of silicon-based detectors is low, the process integration technology is relatively simple. Secondly, silicon has high sensitivity in specific bands, and silicon-based materials have good photon response in the near infrared region, especially high sensitivity in the wavelength range above 300nm, which is suitable for visible light photodetector materials. Although silicon materials have some advantages in performance, they still have obvious limitations for the optical absorption layer materials used as deep ultraviolet photodetectors. The first limitation is determined by the characteristics of silicon material itself. Silicon is an indirect band-gap material with a band-gap energy of about 1.12eV, which makes it have a good photon response in visible and near-infrared bands. However, the energy of incident photons in deep ultraviolet band is much higher than that of silicon, resulting in the photon energy being absorbed by the shallow layer, and photogenerated charge carriers cannot be effectively collected [8]. This results in poor response in the ultraviolet band, which limits the sensitivity and responsiveness of deep ultraviolet photodetectors. At the same time, due to the strong response of silicon to visible light and near infrared, unnecessary background noise will be generated when the silicon-based photodetector is used for detection, which reduces the signal-to-noise ratio of the detector. Therefore, the silicon-based deep ultraviolet photodetector needs to be equipped with a filter system to shield the photons in the non-deep ultraviolet band in practical applications, which increases the complexity and cost of the silicon-based deep ultraviolet photodetector. In dark conditions, the dark current of silicon-based deep ultraviolet photodetectors is strong, which mainly comes from intrinsic defects of silicon materials and thermal excited carriers, which leads to low detection accuracy of photodetectors in dark environments.

2.3. Application of wide-band gap semiconductors in deep ultraviolet detectors

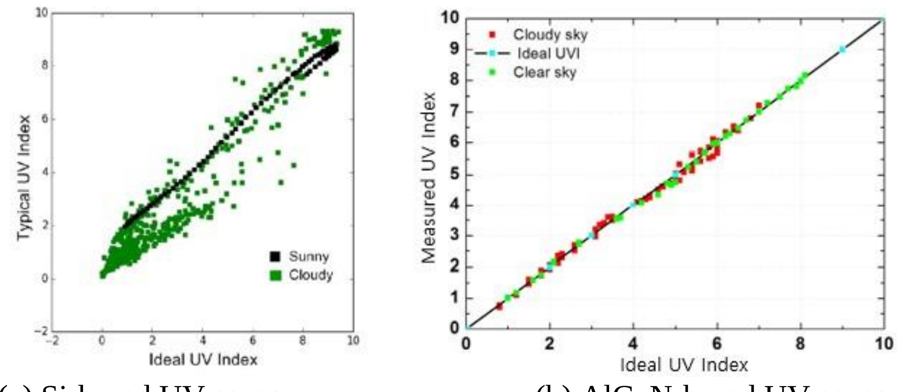
Wide-band gap semiconductor materials usually refer to materials with a bandgap energy greater than 3.5eV, and this type of material has a high absorption efficiency and photoelectric conversion efficiency in the deep ultraviolet band. Typical wide-band gap semiconductor materials include gallium nitride, zinc oxide, gallium oxide and aluminum gallium nitrogen. Deep ultraviolet photodetectors based on wideband gap semiconductor materials have some advantages due to their own characteristics. Wide bandgap semiconductor materials exhibit high responsiveness in the deep ultraviolet range and possess large bandgap energies. In the deep ultraviolet band, the energy of incident photons is greater than the bandgap energy of the material, and the photons can be effectively absorbed and generate electron-hole pairs, which are rapidly separated in the material and form photogenerated current. Thus, the photodetector exhibits high responsiveness in deep ultraviolet band [9]. Moreover, the response of wide-band gap material to visible light band is low, so the deep ultraviolet photodetector made of wide-band gap semiconductor material has a good blind zone characteristic to visible light, which greatly reduces the interference of visible light, making it very suitable for applications requiring accurate detection of deep ultraviolet signals. At the same time, due to the low intrinsic carrier concentration of the wideband gap semiconductor material, the dark current is reduced, and the signal-to-noise ratio is improved, so that the detection accuracy is higher under the low light environment. Wideband gap semiconductor materials such as gallium nitride and other materials have excellent chemical stability and thermal stability, so that the photodetector based on wideband gap semiconductor materials can maintain stable photoelectric performance under high temperature and pressure, strong radiation and strong corrosion environment, and high detection accuracy in harsh environments [10]. Therefore, the application of wideband gap semiconductor materials in deep ultraviolet photodetectors shows significant advantages, such as high responsiveness, low dark current, visible light blind characteristics and high environmental stability, making it very suitable for deep ultraviolet detection scenarios under different environments and requirements, and with high accuracy.

3. Comparison of UV sensor properties of different materials and influencing factors of material selection

3.1. Properties of UV sensors of different materials

Currently available commercial deep ultraviolet (DUV) devices, mainly photodetectors, still have some issues, such as poor selectivity and stability. For instance, silicon, as an indirect bandgap material, has low sensitivity in the ultraviolet and deep ultraviolet wavelength ranges, while showing high response in the visible spectral range. Additionally, silicon requires auxiliary cooling tools and multi-layer structures to achieve sufficient performance, which results in complex manufacturing processes. Wide bandgap semiconductors (WBGSs) with a bandgap ≥3.5 eV are considered potential candidates for DUV optoelectronic devices, including photodetectors. Gallium nitride (GaN) and its alloys with aluminum nitride (AlN) are among the most important direct wide bandgap semiconductors for use in DUV optoelectronics and electronic devices, as well as in high-frequency and high-power applications. Their distinct characteristics, including high electron mobility and superior chemical and thermal stability, enable them to function effectively in demanding environments.

UV index monitoring is one of the uses of UV photodetectors, through which This paper can detect the UV radiation intensity (UV index) that produces sunburn in a specific place and time. In the context of global warming, UV index monitors have good development prospects, driven by market demand, the portability and accuracy of UV monitors are gradually upgraded, but how to further improve its accuracy and reduce costs is still a problem This paper need to consider. In this problem, changing the material of the UV sensor is one of the solutions [11]. Fig.2 compares the measurement accuracy of UV index monitors based on silicon (Si) and aluminum gallium nitrogen (AlGaN) materials.



(a) Si-based UV sensor (b) AlGaN-based UV sensor

Fig 2. Comparison of UV index monitoring of different materials [11]

According to Fig.2 (a), this paper can find that the data obtained by the silicon-based UV index monitor has obvious discretization, and the distribution of data points is scattered. Especially under cloudy conditions, the measured value of UV index deviates greatly from the ideal value, indicating that there is a large error in the accuracy of the silicon-based UV sensor. Fig.2 (b) is a UV index monitor based on aluminum gallium nitrogen. The measured value obtained on sunny and cloudy days is very close to the ideal value, and the data is distributed near the ideal curve. The curve consistent with the ideal curve can be obtained by linear fitting of the data by least square method. This shows that the UV index monitor based on aluminum gallium nitrogen can provide high accuracy measurement data under both sunny and cloudy conditions. Through the comparison in Figure 1, This paper can intuitively find that different materials have a great impact on the accuracy of the sensor, and the accuracy of the UV sensor based on aluminum gallium nitrogen is much higher than that of the silicon-based UV sensor. However, for the choice of UV sensor materials, This paper also need to consider the cost and integration of different materials. Silicon-based optical sensors can be integrated into a single chip, with good integration and relatively low cost, but with low accuracy. So, if we want to further develop UV photodetectors, we can start by improving the sensitivity of silicon-based detectors in the UV and DUV wavelength ranges.

3.2. Influencing factors of material selection

When analyzing material selection such as deep ultraviolet photodetectors, This paper need to consider the influencing factors of different material selection. The factors influencing material selection can be considered from several perspectives, including the cost of the material, the degree of integration, and the balance of accuracy and stability of the photodetector based on the material.

Cost is an important consideration in the selection of materials such as deep ultraviolet photodetectors. Silicon-based materials are widely used in the market because of their mature processing technology, relatively low production cost, and low cost of raw materials. The technology of silicon-based photodetectors in the microelectronics industry is very mature, which makes the processing cost of silicon-based photodetectors relatively low, and the process integration technology is quite simple [9]. In contrast, wide-gap semiconductor materials such as gallium nitride and its alloys have excellent properties as deep ultraviolet photodetector materials, such as high responsiveness in deep ultraviolet bands, visible light blindness, low dark current and good chemical stability, and thermal stability. These properties make wideband gap semiconductor materials a potential candidate for deep ultraviolet photodetectors. However, the production and processing costs of these talents are relatively high. Especially in the case of high precision and high stability requirements, the cost of making photodetectors based on wide-band gap semiconductors is more expensive [12].

In the analysis of integration, silicon-based materials also have obvious advantages at this point. Silicon-based photodetectors can be integrated into a single chip to achieve good integration, and because the process integration technology of silicon-based photodetectors is very mature, the highly integrated production process is relatively perfect and easy to operate. However, although wide-band gap materials are more suitable for working in deep ultraviolet bands, these materials still face many challenges in terms of integration. These wide-gap semiconductor materials usually require more complex manufacturing processes and processing equipment, which greatly increases the complexity and cost of photodetector systems.

In deep ultraviolet photodetectors, the choice of materials has a direct impact on the accuracy and stability of the photodetectors. Silicon-based materials are highly responsive to visible and near-infrared wavelengths, which leads to unnecessary background noise, thereby reducing the signal-to-noise ratio, which affects the accuracy and stability of deep ultraviolet photodetectors under complex conditions. Often to improve the accuracy and stability of silicon-based deep ultraviolet photodetectors, we will be equipped with complex light filtering systems in practical applications, which increases the complexity and cost of the system. In addition, the dark current of silicon-based detectors in dark environments is strong, which leads to poor accuracy of detectors in low light conditions, as shown in Figure 1. In contrast, wideband gap semiconductors have higher photoelectric response and accuracy in deep ultraviolet bands and can provide high-precision measurement data in a variety of environmental conditions, such as sunny and cloudy days. Therefore, from the point of view of accuracy and stability, choosing GaN or AlGaN materials is more advantageous, but there is a trade-off between high cost and low integration.

4. Conclusion

In this paper, the material selection and performance optimization of deep ultraviolet photodetector are analyzed in detail. With the development of science and technology, deep ultraviolet photodetectors have been widely used in the fields of environmental monitoring, biomedical imaging, military reconnaissance and space exploration. However, the existing technology faces many challenges such as response speed, sensitivity, accuracy and so on, especially the stability problem in complex environments. By comparing the photoelectric properties and detector performance of different materials, such as silicon-based materials and wideband gap semiconductor materials, this paper explores how to strike a balance between cost, integration, accuracy, and stability to optimize the performance of deep ultraviolet photodetectors. Wide-band gap semiconductor materials, such as gallium nitride and aluminum gallium nitride, show great application prospects due to their excellent chemical and thermal stability, high responsiveness and low dark current in deep ultraviolet bands.

In summary, although silicon-based materials have advantages in cost and integration, they have significant performance limitations in deep ultraviolet photodetection applications. In contrast, wide-band gap semiconductor materials perform well in improving the accuracy and stability of deep ultraviolet photodetectors, but their production costs are high, the processing process is relatively immature, and the integration is difficult. Therefore, in the selection of materials, the application scenario and accuracy requirements of the deep ultraviolet photodetector made of the material should be considered, and the deep ultraviolet photodetector with different needs can be comprehensively balanced and selected between cost, integration, accuracy and stability. At the same time, future research should focus on how to reduce the production cost of wide-band gap semiconductor materials, improve its integration process, and explore other better structures and materials of deep ultraviolet photodetectors, and through these ways to improve the performance and application range of deep ultraviolet photodetectors.

References

[1] Fang W, Li Q, Li J, et al. Deep ultraviolet photodetector: materials and devices. Crystals, 2023, 13(6): 915.

[2] Kalra A, Muazzam U U, Muralidharan R, et al. The road ahead for ultrawide bandgap solar-blind UV photodetectors. Journal of Applied Physics, 2022, 131(15).

[3] Hao J, Li L, Gao P, et al. Deep ultraviolet detectors based on wide bandgap semiconductors: a review. Journal of Nanoparticle Research, 2023, 25(4): 81.

[4] Alamoudi H, Xin B, Mitra S, et al. Enhanced solar-blind deep UV photodetectors based on solution-processed p-MnO quantum dots and n-GaN p–n junction-structure. Applied Physics Letters, 2022, 120(12).

[5] Nakagomi S. Ultraviolet Photodetector Based on a Beta-Gallium Oxide/Nickel Oxide/Beta-Gallium Oxide Heterojunction Structure. Sensors, 2023, 23(19): 8332.

[6] Colinge J P, Colinge C A. The PN junction diode. Physics of Semiconductor Devices, 2002: 95-137.

[7] Sproul A. Understanding the pn Junction. Solar Cells: Resource for the Secondary Science Teacher, 2003, 73.

[8] Li Y, Zheng W, Huang F. All-silicon photovoltaic detectors with deep ultraviolet selectivity. PhotoniX, 2020, 1: 1-11.

[9] Yoder M N. Wide bandgap semiconductor materials and devices. IEEE Transactions on Electron Devices, 1996, 43(10): 1633-1636.

[10] Sang L, Liao M, Sumiya M. A comprehensive review of semiconductor ultraviolet photodetectors: from thin film to one-dimensional nanostructures. Sensors, 2013, 13(8): 10482-10518.

[11] Son J. UV detectors: status and prospects. UV and Higher Energy Photonics: From Materials to Applications 2018, 2018, 10727: 12-20.

[12] Rogalski A, Bielecki Z, Mikołajczyk J, et al. Ultraviolet photodetectors: From photocathodes to low-dimensional solids. Sensors, 2023, 23(9): 4452.