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High-Responsivity ZnS Schottky Barrier Photodiode Array for Ultraviolet Imaging*

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Abstract: A different approach, using the molecular beam epitaxy (MBE)-grown ZnS-based Schottky photodiode technology, is applied to fabricate an 8×8 photodiode array. The micro-processing procedures of this photodiode array including standard photolithography, a number of metallisation, wet-chemical etching and SiO_2 deposition for insulation are developed. The detector is characterized to have a cutoff wavelength at 340 nm and the photo-responsivity measurements on the pixels result an ultraviolet (UV) response as high as 0.15 A/W, corresponding to an external quantum efficiency of 55% in the visible-blind spectral ranging from 400 down to 250nm. Imaging tests indicate that this array is able to capture the intensity profile of a given UV light source with reasonably good capability.

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1 Introduction

Ultraviolet (UV) photodetectors with high responsivities for wavelengths shorter than 400 nm are very important for applications in the fields of UV astronomy, environmental and biological sciences as well as in medical instrumentation. Although the modern semiconductor UV detectors are mainly fabricated using Si, there is an increasing interest in developing GaN alloy[1,2] and diamond thin films[3] for visible-blind and solar-blind UV detection applications in recent years. But problems still exist for these detectors regarding the structures and materials used. Diamond of a good enough quality is not readily available and appropriate technology is far from being mature. The most difficult problem for GaN-based UV detector researchers is the lack of a lattice-matched substrate. As a result, a high density of misfit dislocations and traps is inevitably present in these structures[4], severely limiting the response time of the detectors. It is well known that ZnS-based II-VI wide bandgap semiconductors enjoy the advantages of being highly resistive, UV light sensitive and having low dark noise, and are potentially good candidates as visible-blind UV imaging materials. The authors have recently demonstrated a ZnSSe-based Schottky barrier photodetector fabricated on GaP (100) substrate using the molecular beam epitaxy technique[5]. This novel device has high external quantum efficiency, a visible rejection power of more than three orders of magnitude, sharp cutoff wavelength tunable from 400 to 340nm, very low

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dark current density and fast response time. Additionally, at 8.8% Se concentration, it is lattice-matched to Si and thus is compatible with the advanced Si integration technology. In this work, we focus on the fabrication and characterization of a ZnS-based Schottky photodiode array which consists of a 340nm Al-doped ZnS layer followed by a 380nm intrinsic ZnS layer. The purpose of this study is to realize a workable approach using various microelectronic processing to fabricate the photodiode array and to investigate its photoresponse and capability of imaging.

2 Device fabrication

The Ⅱ-Ⅵ epitaxial thin films were deposited on GaP (100) substrates using a VG V80H MBE system. Before GaP wafers were loaded into the MBE chamber, the substrates were first degreased with boiling trichloroethylene for 3min and then rinsed in solution of NH_4OH: H_2O_2: H_2O for 10min. After being baked dry with nitrogen gas, they were loaded into the MBE growth chamber. Prior to the deposition, the substrates were cleaned according to the Asami *et al*. method[6]. All the substrates were adhered to the sample holder by applying gallium on their backsides. For the growth of ZnS photodiode array, ZnS and Al sources were used, which were contained in separate effusion cells. After loading the sources, the chamber should be baked for a few days to remove the absorbed contaminants as much as possible. The Al cell was used as the *n*-type dopant source for the growth of the bottom electrode layer and the cell temperature was fixed at 860℃ which gives the high dopant activation for the ZnS layer. The electronic transport properties of as-grown epilayers were determined by Hall-effect measurements using the Van der Pauw method. Indium was used for making ohmic contacts and was verified before the measurements. Magnetic-field strength of 0.8T and current of 1mA were used. The measurements carried out at room temperature indicated that the electron carrier density as high as $1\times10^{19}cm^{-3}$ with the carrier mobility of $56.4cm^2/(V\cdot s)$ was achieved in the Al-doped ZnS layer. It is worth pointing out that in our pervious work, we have observed that good Al dopant activation can only be achieved for the ZnSSe alloy with Se composition less than 50%. However, this doping difficulty does not pose a major obstacle to the potential application of the ZnSSe alloy as an range of Se composition lies between 0~36% (assuming the longest turn-on wavelength at 400nm).

An 8 × 8 array of mesa-type transparent Schottky barrier detectors were then fabricated. Figure 1 shows the top view of the photodiode array. Using standard photolithography procedures and chemical etching method the mesa structures

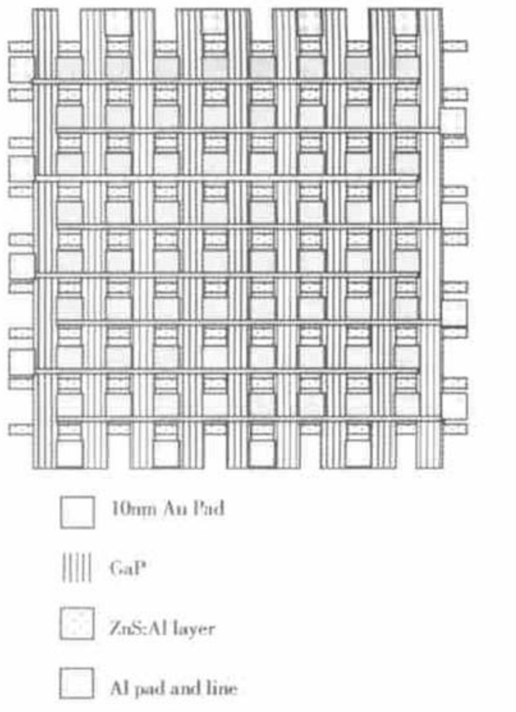

Fig. 1 Top view of the photodiode array

with effective pixel area of 200μm × 200μm were defined. First an 8×8 semi-transparent Schottky Au contacts array of 10 nm thick was deposited on the intrinsic ZnS layer using thermal evaporation technique. Then etching to the GaP substrate and to the *n*-type ZnS layer was carried out sequentially to separate the pixels into columns and rows. For the fabrication of the eight ohmic contact pads, wet-chemical etching was firstly applied to expose the bottom n-type ZnS layer, then a 200nm-thick In layer was deposited to form the ohmic contact. The insulation between the rows and columns was made by depositing a 0.5μm layer of silicon dioxide using a thin film sputtering system (Denton DVI SJ/24LL). Finally, Al was sputtered on the ohmic contacts, and Au pixels in the same row were interconnected via an Al line to the Al Schottky bonding pad. The side view of a single pixel of the photodiode array is displayed in Fig. 2.

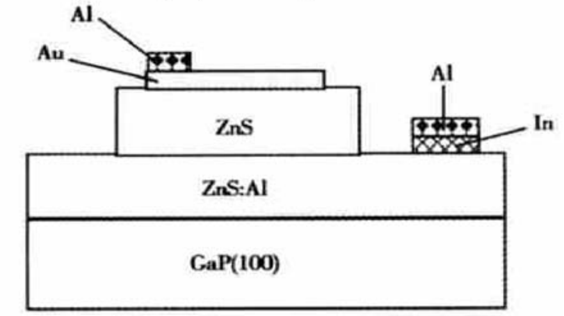

Fig. 2 Schematic side view of a single pixel of photodiode array

3 Device characterization

The photoresponse measurements on the finished device were carried out using a 180W xenon arc lamp as the light source. The light beam was first dispersed using a monochromator and then focused on the cell area. At each wavelength, the power of the light incident on the mesa was carefully measured using a Newport 835 optical power meter that uses a UV-enhanced Si photodiode (818UV) as the detector. The spectral response of this power meter had been calibrated by the manufacturer. The short circuit photocurrent was measured as a function of the wavelength of the incident photons using a digital current meter (Keithley Model 237) with high sensitivity and precision. In order to avoid the second-order effect of the monochromator, a low-pass filter with a cutoff wavelength at 420nm was used in measuring the photoresponse for the long-wavelength region.

The room temperature spectral responsivity of a typical pixel within the fabricated detector array is shown in Fig. 3. The responsivity has a rather sharp transition. For wavelength longer than 450nm, the response is down from the peak response by more than 3 orders of magnitude, showing very good visible rejection. In fact, for wave-

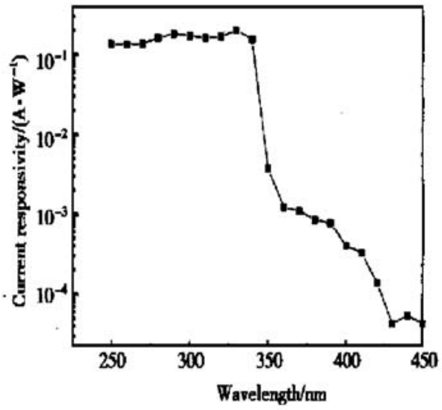

Fig. 3 Photocurrent responsivity of array pixel as a function of incident photon wavelength

length longer than 450nm, the response current reached the limit of the sensitivity of current meter so the actual visible rejection power of the detector could be even better. This array is therefore suitable for use in visible-blind applications. A better visible rejection power of more than 4 orders for wavelength longer than 420nm can be obtained with our regular ZnS photodiodes, which has been demonstrated previously[5]. We suspect that the relatively poor performance in terms of the visible rejection of the detector array is possibly due to either a non-ideal MBE growth condition or the imperfection of the device processing. The response shows a cutoff at 340nm which corresponding to the band edge of the intrinsic active layer and reaches a responsivity value as high as 0.15A/W. This value corresponds to an external quantum efficiency of 55% in the UV region. Since the reflection loss is measured to be around 30%, with the application of an antireflection coating, a higher efficiency should be realizable with this ZnS-based Schottky photodiode array.

The experimental setup used for testing the capability of imaging of the 8×8 photodiode array consists of an UV source, focusing lens, and a high precision current meter. An output of 330nm from the monochromator was selected as the excitation source. Several patterns were used and the photocurrent signals generated from all the 64 pixels were measured. Figure 4 shows the intensity distribution among the 64 pixels upon the 330nm UV source illumination with a "L" shape as the testing pattern. The resulting intense contrast shown in the figure clearly indicates that the array is able to capture the intensity profile of a given UV light source with reasonably good capability.

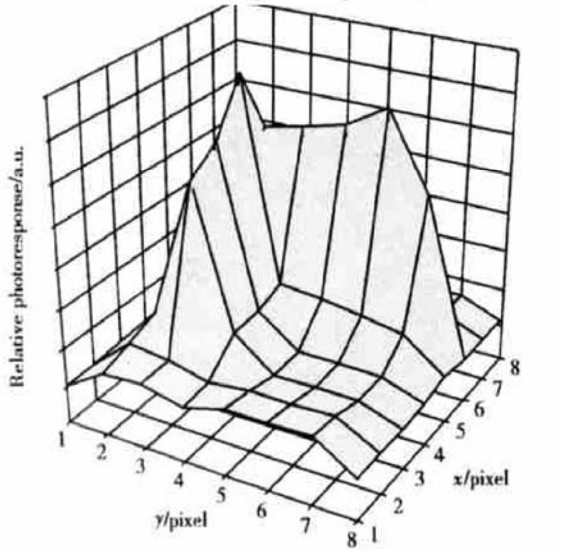

Fig. 4 Intensity distribution from image with a "L" shape pattern

4 Conclusion

Regarding to a different approach, a novel 8×8 photodiode array based on the MBE-grown ZnS-based Schottky barrier diode structure was fabricated. Newly developed micro-electronic processing scheme, including standard photolithography, a number of metallisation, wet-chemical etching and SiO_2 deposition for insulation were used in the device fabrication. The device was measured to have a responsivity as high as 0.15A/W at wavelength of 340nm, corresponding to an external quantum efficiency of 55%. The responsivity remained nearly constant for wavelengths from 250nm to 340nm and dropped by three orders of magnitude for wavelength longer than 450nm. Imaging test performed on the array shows that high quality imaging can be achieved through this array. This work is an encouraging first step in the development of larger and more practical ZnS-based imaging arrays for visible-blind UV imaging applications.

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紫外成像用高响应 ZnS 肖特基光电二极管阵列*

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摘要: 基于分子束外延(MBE)生长技术,制备出了新颖的 8×8 ZnS 肖特基光电二极管阵列,研究了制备该器件的标准光刻,金属沉积,湿化学腐蚀,SiO_2 绝缘层沉积等一系列微电子处理工艺.该肖特基光电二极管阵列的光谱响应截止边为 340nm.在 400~ 250nm 的可见光盲区域,光电响应测试显示该器件在截止边波长处具有 0.15A/W 的高响应度,相对应的量子效率为 55%.成像测试显示该器件具有良好的紫外成像特性.

关键词: ZnS 肖特基; 光电二极管阵列; 分子束外延; 高响应度

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沈大可 男, 博士研究生, 现从事 ZnS(Se)基光盲紫外器件的研制工作.

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