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Editorial

Nanostructured Wide-bandgap Semiconductors for Ultraviolet Detection

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When a light is illuminated on a semiconductor, the electrical conductivity will increase due to the generation of additional free electrons and holes in the semiconductor. Therefore, the increased electrical current change will be detected in the circuit containing the semiconductor or a voltage drop change on the semiconductor will be generated [1]. Photodetector is normally such a device whose electrical properties are sensitive to the light illumination.

A semiconductor is sensitive to a certain spectral band due to the intrinsic bandgap energy. Ultraviolet (UV) detectors denote those devices showing spectral response with wavelength short than 400 nm, which can be widely applied in various fields such as flame sensing, medial phototherapy, missile warning, radiation detection, astronomical studies, optical communications and electronic industry [2]. Generally, UV light is typically divided into four spectral regions: UV-A (for wavelengths between 400 and 320 nm), UV-B (for wavelengths between 320 and 280 nm), UV-C (for wavelengths between 280 and 200 nm), and far UV (for wavelength between 200 and 10 nm, which reaches the X-ray spectral low energy frontier) [3]. The UV light from the sun reaching the earth is very weak due to the absorption by the atmospheric ozone layer. A "solar-blind" UV detector denotes a device not sensitive to the wavelength longer than 280 nm. Another terminology of "visible-blind" UV detector is also often used, which defines the cut-off wavelength at 400 nm [1]. A high-performance photodetector should satisfy the *6S* requirements of high *sensitivity*, high *signal-to-noise ratio*, high spectral *selectivity*, high *speed*, high *stability, and simplicity* [4-6].

Silicon, with a bandgap of 1.1 eV, when used for UV detection, has some limitations, such as the use of pass optical filters to stop low energy photons [7].Wide-bandgap semiconductors such as III-nitrides, SiC, and diamond have been emerging as the advanced materials for the UV detection due to their wide bandgaps [8–10]. These semiconductors exhibit intrinsic visible-blind or solar-blind features as UV detectors. Due to the high optical absorption coefficient or the high-quality single crystal nature of these semiconductors, thin films with submicron thickness were sufficient to achieve the high-performance photoresponse properties.

III-nitrides have the unique features of tailored bandgaps and direct band structures, allowing a high sensitivity to UV light. We developed InGaN metal-semiconductor-metal (MSM) UV photodetectors with a low-leakage current by inserting a 5 nm-thick CaF_2 layer between the metal and the InGaN semiconductor [9]. The dark current was drastically reduced by six orders of magnitude compared with those without CaF_2, resulting in an extremely high discrimination ratio larger than 10^6 between UV and visible light. The responsivity at 338 nm is as high as 10.4 A/W biased at 2V, corresponding to a photocurrent gain of around 40. The electrical current dropped by more than two orders of magnitude within 0.3 s (limitation of the measurement system) once the UV light off, showing little persistent photoconductivity (PPC).

Diamond has a wide bandgap of 5.5 eV, which is very promising as deep-UV (DUV) photodetectors with solar blindness. We developed various kinds of diamond DUV photodetectors such as the interdigitated-finger MSM photoconductor, MSM photodiode, and Schottky photodiode by using thermally stable tungsten carbide electrical contacts up to 500°C. These devices were fabricated on the lightly boron-doped diamond thin film, which was grown on the type-Ib diamond substrates by microwave plasma-enhanced chemical vapor deposition system. A responsivity of 6 A/W at 220 nm with a gain of 33 was obtained. A solar-blind ratio up to 10^8 was achieved without PPC.

Recently, low-dimensional nanostructured wide-bandgap semiconductors are attracting growing attention for UV detectors due to their high crystal quality, large surface-to-volume ratio, and low-cost synthesis method. These nanostructures provide novel opportunities and diversities in developing novel UV detectors than thin films fabricated by vacuum deposition technologies. For the device fabrication, the nanostructures were firstly dispersed on an insulating substrate, then, the electrodes were deposited above the nanostructures to form the photodetector by using photolithography as conducted for thin film semiconductors. One-dimensional single crystal ZnS, ZnSe, and ZrS_2 nanobelts were developed as UV-A detectors [12-14]. The Extremely high UV sensitivity of 7.1×10^5A/W and high-speed of 0.2 μs was achieved at 450 nm [14]. β-Ga_2O_3 nanowires, Zn_2GeO_4 nanowires and $In_2Ge_2O_7$ nanobelts were promising nanostructured semiconductors for solar-blind DUV detection [16-18] due to their wide bandgap energies more than 4.3 eV. Even an individual nanostructure showed more pronounced photoresponse properties than diamond thin film such as high sensitivity or absolute photocurrent upon the DUV light illumination with the same power density. The metal/semiconductor interface barrier, which is modified upon illumination, is critical to

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determine the electrical transport properties for these wide-bandgap semiconductors. Different from the narrow-bandgap semiconductor nanostructures, whose photocurrent is usually dominated by the surface, bulk-dominated photocurrent dynamics were observed in β-Ga_2O_3 nanowires. This was desirable for high-temperature applications [16].

Solution based self-assembly provides an alternative strategy to vacuum deposition of nanothick films for UV detectors [19]. This method is a bottom-up approach, which can be performed under room temperature on flexible substrates, exhibiting methodological simplicity, low cost, and low environmental impact. This approach has the marked advantages of application to any nanostructures, offering a broad materials selection for different UV detections. Since the formation of nanothick thin film structures, the photodetector fabrication can be conducted totally similar to that of vacuum-deposition thin films. ZnO and ZnS nanofilms were fabricated for UV detection, showing appreciated photoresponse properties [21,22]. The grain boundaries, which often degrade the device performance in vacuum-deposition thin films, could be a positive effect to determine the UV photoresponse properties, enhancing the response speed without losing the sensitivity.

Recently, we also proposed and demonstrated the concept of arbitrary multi-color photodetection by hetero-integrated semiconductor nanostructures [23]. Various semiconductor nanostructures were integrated on the wide-bandgap semiconductors or insulator substrates. The visible light, UV light and deep UV light three-band photodetectors were created by integrating ZnO sub-microrods, and CdS nanowires on a diamond layer. Because of the photoresponse of each spectra band is determined by each semiconductor nanostructure or the semiconductor substrate, the detectors can achieve a high spectra selectivity, high sensitivity, high speed, high signal-to-noise ratio, high stability, and high simplicity. Such a way offers the selection of different nanostructures and substrates for different purposes. For example, one can place a PbS nanostructure on diamond for dual-color of infrared and DUV detection, avoiding the complex interface control in multilayer structures, greatly improving the simplicity [24].

In summary, the development of wide-bandgap semiconductors nanostructures has added new members to the traditional UV detectors family. The photoresponse performance is even super to the vacuum-deposition wide-bandgap semiconductors. The push of these nanostructured UV detectors to practical applications strongly depends the synthesis of the nanostructures in a well-controlled manner. Most of the nanostructured wide-bandgap semiconductors photodetectors still stay in the lab. Solution-based nanothick thin film strategy offers encouraging opportunity for the applications, which need further optimization of the fabrication process.

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