



New concept ultraviolet photodetectors

Hongyu Chen¹, Kewei Liu², Linfeng Hu¹, Ahmed A. Al-Ghamdi³ and Xiaosheng Fang^{1,*}

¹ Department of Materials Science, Fudan University, Shanghai 200433, People's Republic of China

² State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, People's Republic of China

³ Department of Physics, Faculty of Science, King Abdulaziz University, Jeddah 21589, Saudi Arabia

Benefiting from the continuous innovations in semiconductor materials and device fabricating techniques, ultraviolet (UV) photodetectors have been successfully used in advanced communications, flame detection, air purification, ozone sensing and leak detection, among others, in the past few decades. Nowadays, nanoscience, nanofabrication technologies and versatile materials have sparked a new vision of UV photodetectors, which move toward higher precision, lower energy consumption and greater miniaturization. This paper is thus mainly focused on the perspective of molding devices through exploring new materials and novel architectures inspired by state-of-the-art UV photodetectors, predicting the direction of next-generation photodetectors. It is expected that new concept UV photodetectors with smart, intelligent and multifunctional design will benefit daily life and the well-being of society in the near future.

Introduction

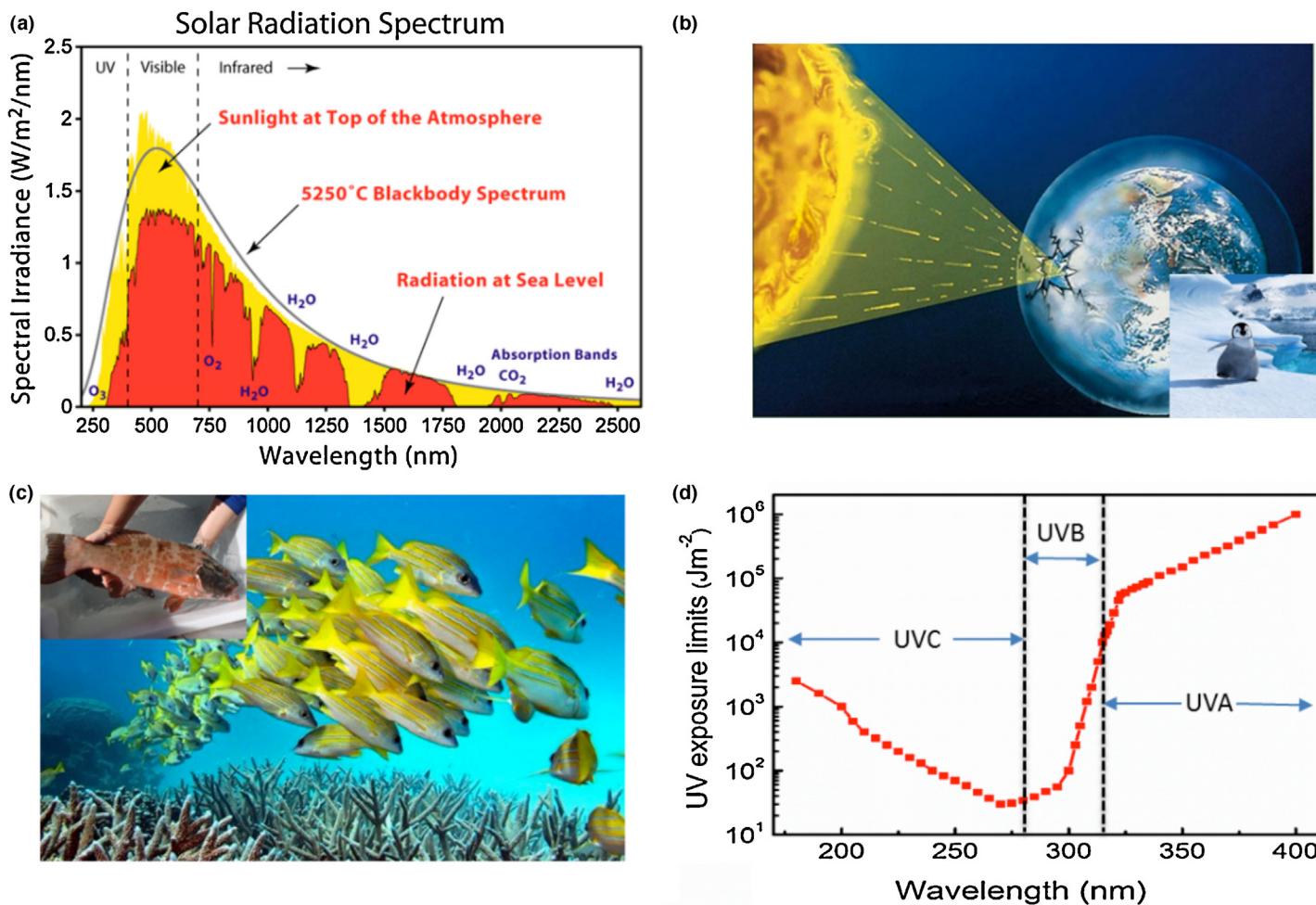
UV radiation has been regarded by many as an important component of the solar radiation since its discovery by Johann Ritter in 1801. Although it only accounts for less than 10% of the total solar radiation (Fig. 1a) [1,2], UV radiation has a profound impact on the survival and development of humankind. For example, moderate skin exposure to natural or artificial UV light is advantageous for health, for instance, facilitating the synthesis of Vitamin D, killing germs, treating or preventing rickets, etc. By contrast, excessive UV radiation can cause various diseases, such as cataracts and skin cancer, and even accelerate the aging process. In addition, the output of crops and the lifespan of buildings are also strongly affected by UV radiation. As most UV radiation can be absorbed by stratospheric ozone, ozone monitoring has been performed since the early 1980s. Recently, anthropogenic-induced decline in stratospheric ozone (Fig. 1b) concentration, concurrently intensifying the UV radiation, has become alarming, and the 'ozone hole' over Antarctica has become larger. The inset of Fig. 1c shows the

coral trout with skin cancer arising from the destruction of the ozone layer.

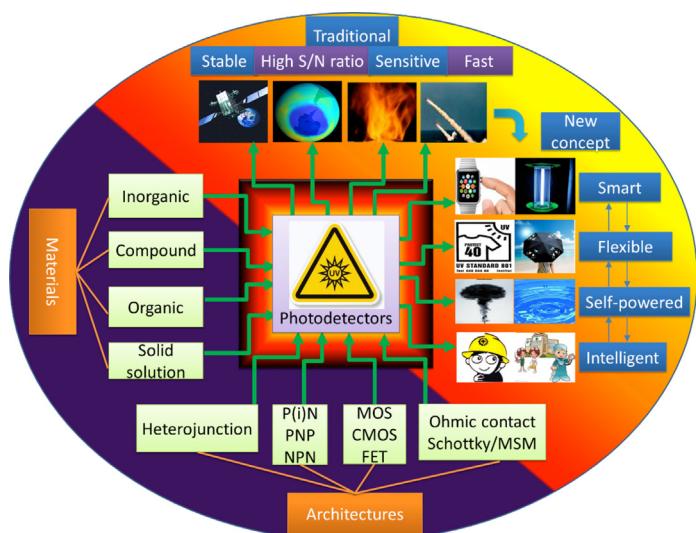
What's more, further research shows that a decline of 1% in the volume of the ozone layer will cause an increase of 2% in UV radiation at ground level, leading to an increase of 3% in the incident rate of skin cancer [3–6]. Therefore, the study of UV photodetection has drawn considerable attention from scientific researchers in the relevant fields.

In terms of UV radiation, the International Commission on Illumination (CIE) has divided the UV spectrum (visible-blind) into three bands: the band with the wavelength range from ~320 nm to 400 nm is designated as UVA, the band with the wavelength range from 280 nm to ~320 nm is designated as UVB and the band with the wavelength range from 100 nm to 280 nm is designated as UVC. The deep UV (DUV) wavelengths from 220 nm to 280 nm are in the solar-blind region, and the wavelengths below 180 nm are in the vacuum UV region. As shown in Fig. 1d, UV radiation limits for human beings are regulated by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). It is noteworthy that UVB and UVC are the strongest and potentially most harmful forms, especially at

*Corresponding author: Fang, X. (xshfang@fudan.edu.cn)

**FIGURE 1**

UV radiation and human beings. (a) Solar irradiation spectrum [2]. (b) The ozone hole over Antarctica. (c) A group of blue-stripe snappers swimming over the staghorn corals, and inset is the plectropomus leopardus with skin cancer. (d) UV exposure limits of human beings as the function of wavelength in the UV regime. Reproduced with permission [3]. Copyright © 2004 Health Physics Society.

**FIGURE 2**

A technology roadmap leading to next generational chip-scale UV photodetectors.

the wavelength of 270 nm; the UV exposure limit of human beings is as low as 3 mJ/cm² in one second [3].

Thanks to Einstein's explanation of the photoelectric effect via the photon hypothesis, semiconductor UV photodetectors for transforming UV radiation signals to electronic signals were subsequently invented. Hence, UV radiation could be easily measured and noticed. As shown in Fig. 2, after more than a century's steady development, modern UV photodetectors share some unique features such as high stability, high sensitivity, high speed, high signal-to-noise (S/N) ratio, among others, which have attracted much attention in recent years for their potential applications in communications, ozone hole monitoring, flame detection, etc. However, as the science advances, the growing needs and expectations from users are exceeding the performances of traditional UV photodetectors, and novel UV photodetectors with some special function or multiple functions have become more and more essential for practical applications. For instance, smart, flexible, self-powered and intelligent UV photodetectors are urgently needed in health, infrastructure, environment monitoring and unattended stations, and so on. Therefore, in the view of both fundamental researches and technological applications, we hereby present some perspectives for fabricating versatile UV

photodetectors, in conjunction with exploring novel materials and device architectures. It is expected that the design concept discussed through this review could lead to inspiration for next-generation UV photodetectors derived from state-of-the-art devices.

To design or fabricate high-performance UV photodetectors, it is essential to understand the physical mechanisms well. Because the schematic structures (heterojunction, *p-n* junction, Schottky junction, and so forth) and device parameters (responsivity, gain, quantum efficiency, response time, bandwidth, gain-bandwidth product, noise equivalent power, among others) have been fairly demonstrated in previous reviews [7–11], they are not presented here. In this paper, we first review some new concept UV photodetectors that have recently emerged from traditional devices, which exhibit various special properties and novel potential applications. Following this, a discussion of the challenges and opportunities for these techniques in practical applications is presented.

Novel nanofabrication techniques and multifunctional UV photodetectors

In the past half-century, the rapid advance in semiconductor optoelectronic devices has transformed our world. The constant outpouring of semiconductor lasers, quantum well lasers and integrated photoelectric devices have benefitted greatly for sophisticated fabrication techniques, such as molecular beam epitaxy (MBE), metal–organic chemical vapor deposition (MOCVD),

pulsed laser deposition (PLD), atomic layer deposition (ALD), magnetron sputtering, among others. These semiconductor fabrication techniques could be used to control the energy band-gap, precisely. Therefore, UV photodetectors without filler come out based on the bulk or thin film of the wide band-gap semiconductor materials such as ZnO, GaN, GaAlN, SiC and diamond, and so forth [12–16].

With the constant improvement of the photoelectric device integration, various methodologies have been developed for fabricating semiconductor nanostructures up to now. Typically, they are grouped into two categories: top-down and bottom-up approaches [17]. Top-down approaches are dimensional reduction by lithography or patterning techniques, such as focused ion beam (FIB), micro-electro-mechanical system (MEMS), nano imprint lithography (NIL), e-beam lithography (EBL) nanotechnology, among others, to prepare patterns of thin films. Bottom-up approaches start with individual atoms and molecules and build up the desired nanostructures, such as nanocubes [18], nanospheres [19], quantum dots [20], nanobelts [21] and solution based low-temperature nano thin films [22], and so on. The synthesis usually involves chemical vapor deposition (CVD), vapor–liquid–solid (VLS)/vapor–solid (VS) processes, hydrothermal/solvothermal reaction, solution-based self-assembly, template-assisted growth and subsequent heat-treatment processes, etc. Benefiting from these low-cost and simple manufacturing processes, various novel wide band-gap semiconductor nanomaterials (Fig. 3) with dimensions of 1–100 nm have

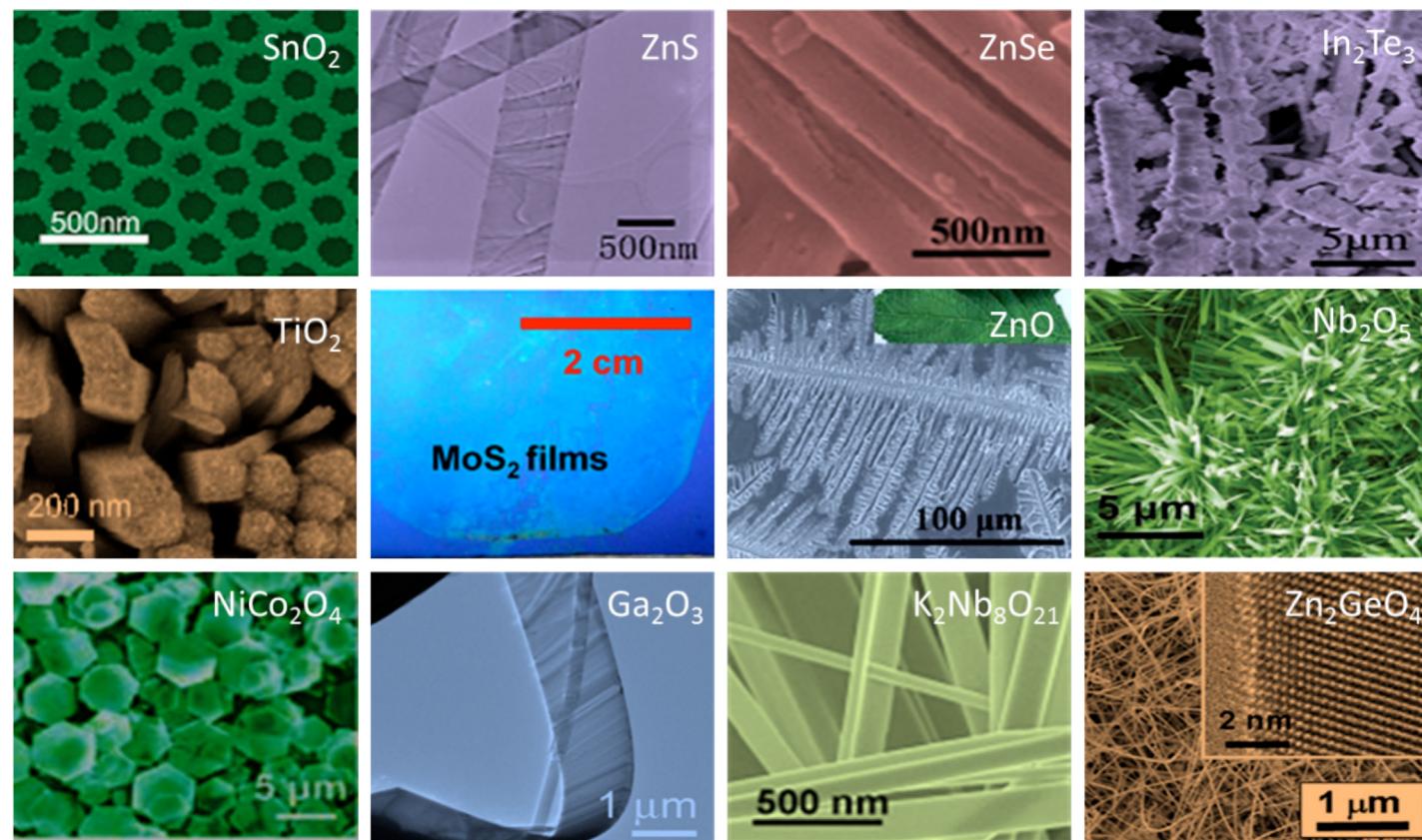
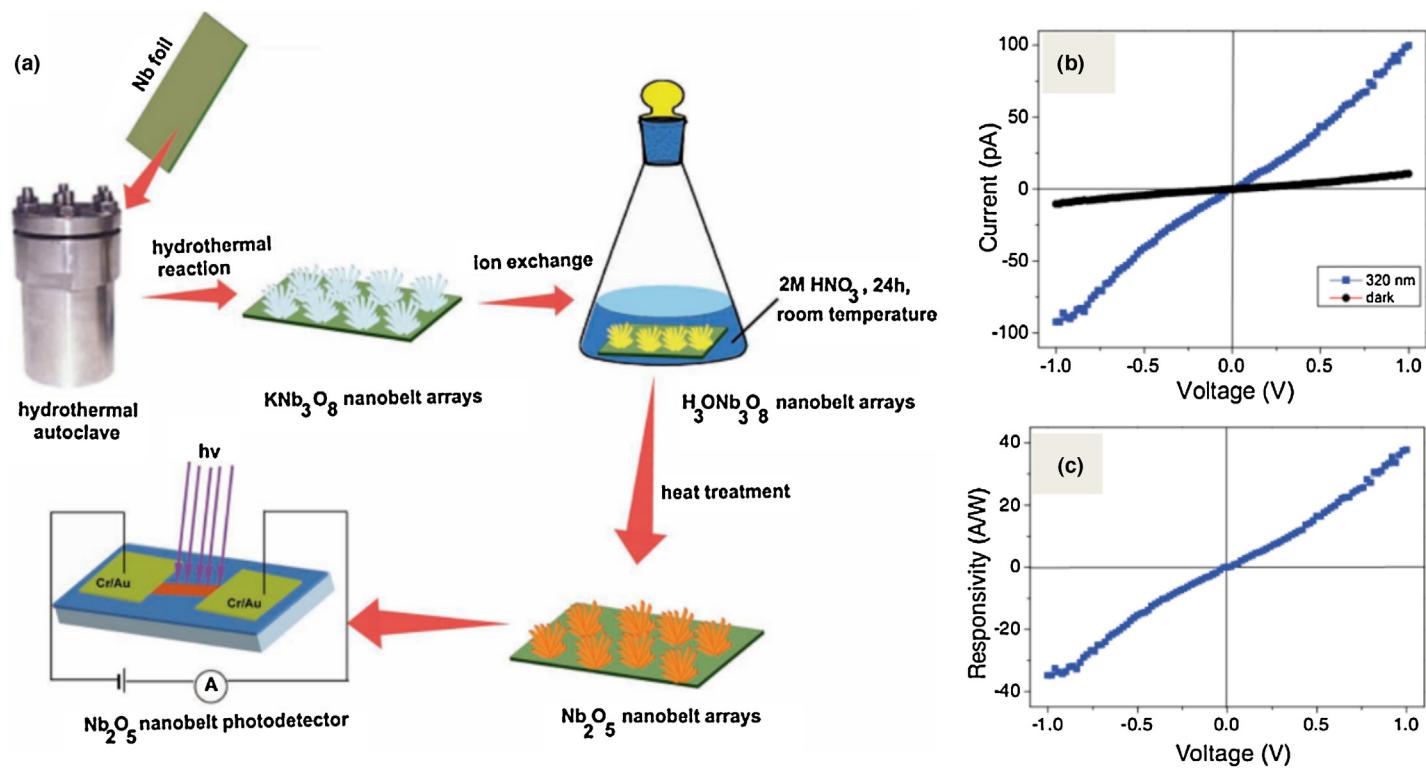


FIGURE 3

SEM images of the representative wide band-gap semiconductor nanostructures used for UV photodetectors. Reproduced with permission [21,25–31,34–37]. Copyrights: © 2012 WILEY-VCH (SnO_2), © 2009 WILEY-VCH (ZnS), © 2009 WILEY-VCH (ZnSe), © 2012 American Chemical Society (In_2Te_3), © 2014 Institute of Physics (TiO_2), © 2013 American Chemical Society (MoS_2), © 2013 Royal Society of Chemistry (ZnO), © 2011 WILEY-VCH (Nb_2O_5), © 2011 WILEY-VCH (NiCo_2O_4), © 2014 Wiley-VCH (Ga_2O_3), © 2014 WILEY-VCH ($\text{K}_2\text{Nb}_8\text{O}_{21}$), © 2010 American Institute of Physics (Zn_2GeO_4).

**FIGURE 4**

(a) Schematic illustration of the fabrication procedure of Nb_2O_5 nanobelt photodetector. (b) I - V characteristics of an individual Nb_2O_5 nanobelt-based photodetectors illuminated by 320 nm light and under dark conditions. (c) The responsivity versus applied-voltage characteristic under illumination of 320 nm light. Reproduced with permission [30]. Copyright (2011) WILEY-VCH.

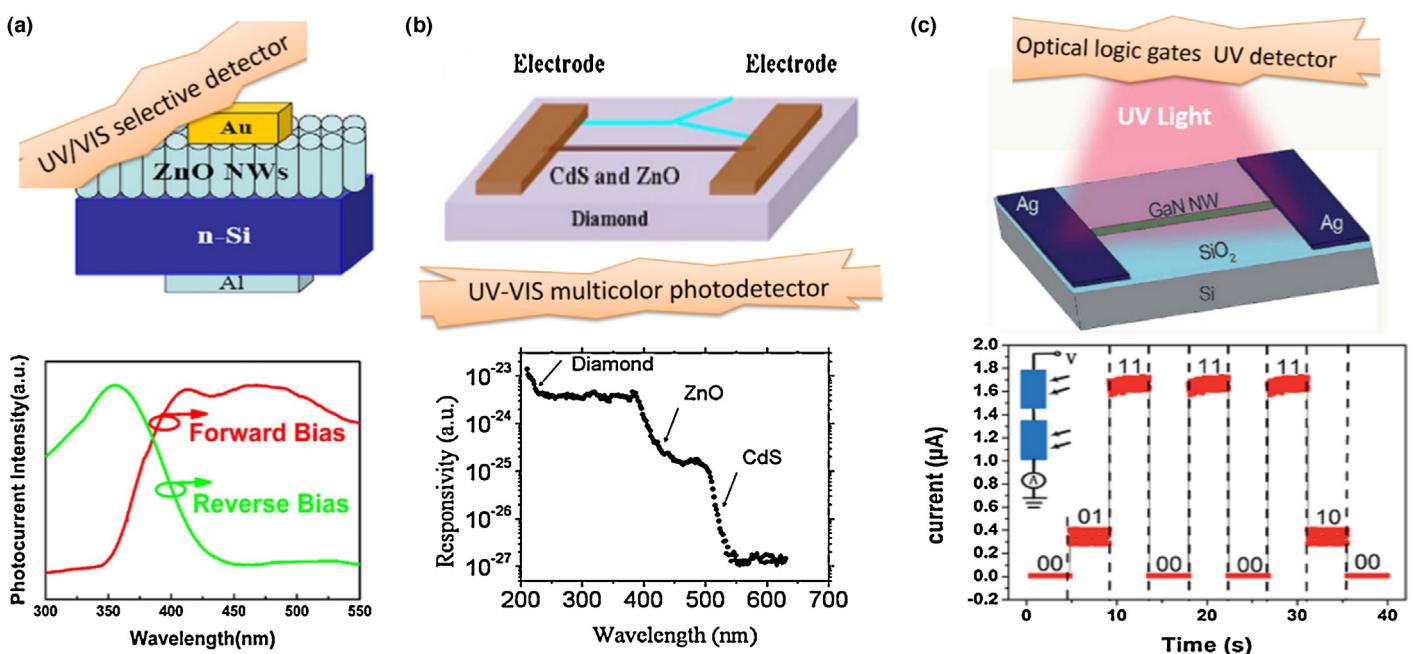
been explored for fabricating UV detectors, such as SnO_2 , ZnS , ZnSe , $\text{In}_x\text{Te}_{3-x}$, TiO_2 , MoS_2 , ZnO , Nb_2O_5 , NiCo_2O_4 , Ga_2O_3 , $\text{K}_2\text{Nb}_8\text{O}_{21}$ and Zn_2GeO_4 [21,23–37]. Because of the scaling down of the effective conductive channel caused by the nanostructures' high surface-area-to-volume ratios, these nano-photodetectors usually show a higher responsivity and photoconductivity gain. To demonstrate it vividly, an Nb_2O_5 nanobelt UVA detector is taken as an example, and the details of its fabrication process and the photoelectric properties will be presented in the next section.

Niobium pentoxide (Nb_2O_5) is one of the most important transition metal oxides. With a band-gap of ~ 3.4 eV, it is an ideal candidate for visible-blind UV-light sensors, especially in the UVA band. As illustrated in Fig. 4a, a facile yet versatile route has been developed to synthesize self-assembled Nb_2O_5 nanobelts through a bottom-up approach. Firstly, a niobium (Nb) foil (99.99%) is polished, ultrasonically cleaned and dried under flowing N_2 . Then, it is immersed in a KOH solution in an autoclave, heated to 170°C for 16 hours and afterwards cooled naturally to room temperature. The product is subsequently immersed in a HNO_3 solution for 24 hours at room temperature. After undergoing ion exchange, it is calcined for 3 hours at 650°C under Ar flow to obtain a white product consisting of Nb_2O_5 nanobelts. And the as-grown Nb_2O_5 nanobelts are detached from the Nb foil ultrasonically in ethanol and a drop of this dispersion is dried on a Si substrate with a SiO_2 top layer. The Cr/Au electrodes are patterned on the top of the nanobelts using photolithography, electron-beam deposition and the lift-off process. The as-fabricated detector shows excellent optoelectronic properties, as shown in Fig. 4b and c, the annealed Nb_2O_5 nanobelt photodetector with better crystallinity shows an

enhanced photocurrent under 320 nm UV-light illumination with a smaller dark current. Fig. 4c displays the responsivity versus applied-voltage characteristics under illumination of 320 nm light. The spectral response at 320 nm is about 37.8 A/W at a bias of 1 V, corresponding to an external quantum efficiency as high as 15,095% [30]. This means that the potential applications of nanotechnology for fabricating ultra-compact UV detectors are considerably reliable. Although research is still in the prototype stage, it is believed that nanotechnology could pave a possible way for exploring nanoscale wavelength selective UV photodetectors with novel optical and electronic properties. Moreover, the novel nanostructure UV photodetector could be combined with other functions. For instance, Fig. 5a is a visible (VIS)/UV alternative photodetector based on ZnO nanowells fabricated on the n -Si substrate [38], Fig. 5b is a UV-VIS multicolor photodetector fabricated by CdS and ZnO nanowells on the diamond substrate [39], and Fig. 5c is an optical logic gates UV detector realized by the nonpolar a -axial GaN nanowire [40].

Opportunities and challenges for plasmonics enhanced UV photodetectors

As shown in Fig. 6a, nanoscale electronic devices still face interconnection delay issues. By contrast, the sizes of photonic devices with high information processing speed are limited to micron-dimensions by the law of optical diffraction. Thus, as an important optoelectronic device, it has been challenging for UV photodetectors to operate in the form of nanoscale devices at optical frequencies. Fortunately, a candidate technology that has emerged, as surface plasmon-polaritons (SPPs) supported by

**FIGURE 5**

Versatile photodetectors fabricated by band-gap engineering techniques. (a) Visible (VIS)/UV light alternative photodetector based on *n*-ZnO NWs/*n*-Si. Reproduced with permission [38]. Copyright © 2008 American Institute of Physics. (b) UV-VIS multicolor photodetector fabricated by CdS and ZnO nanowell on the Diamond substrate. Reproduced with permission [39]. Copyright © 2013 Nature Publishing Group. (c) UV detector and optical logic gates based on nonpolar *a*-axial GaN nanowire. Reproduced with permission [40]. Copyright © 2014 Royal Society of Chemistry.

metallic nanostructures (NPs), may provide new opportunities to bridge the gap between the worlds of nanoscale electronics and microscale photonics [41–45].

SPPs are collective oscillations of free electrons between metal and dielectric (semiconductor) materials. This provides a unique ability to concentrate, route and manipulate light at the nanoscale [46], and this has been employed to enhance the performance of UV photodetectors. As shown in Fig. 6b, ZnO nanowires based UV detectors can attain giant enhancements in photoresponsivity and response speed while the dark current decreases by two orders of magnitude resulting from the Au nanoparticles at the same time [47]. Similar to this result, the responsivity of the GaN UV detectors with annealed Ag nanoparticles can be enhanced nearly 30 times relative to plain GaN (Fig. 6c) [48]. Moreover, localized surface plasmon resonance (LSPR) and propagating surface plasmon (PSP) based on various metallic nanostructures (Fig. 7a) [49], such as metallic nanoparticles (Fig. 7b) [50], individual nanogap electrodes (Fig. 7c) [51], nanoantennas (Fig. 7d) [52], waveguides (Fig. 7e) [53], graphene-antenna sandwich structures (Fig. 7f) [54], coaxial hole structures (Fig. 7g) [55,56], among others, have been applied in solar cells and photodetectors at visible, IR and terahertz frequencies, exhibiting remarkable advantages [41] including (1) higher integration densities through shrinking the size of detectors, (2) low device capacitance for fast transition times, allowing for higher band width operation and (3) reduced operation energy, owing to the enhanced light matter interactions.

Although evidence of enhanced performance in UV detectors resulting from nanostructures has been reported, the intrinsic physical mechanism is still ambiguous. The large energy mismatch between surface plasmons and wide band-gap semiconductors is a major problem that has not been solved. At any rate, the potential

value of SPPs in UV detectors is indeed attractive. Recently, with the development of plasmonics, researchers have found that high-order multipoles (dark mode) can satisfy the requirements of energy match in the UV region, and it could interact with far field directly due to the interference inside the plasmon's system [57–63]. Thus, there may be a novel path through the 'darkness' toward a bright future for plasmonics in conjunction with UV detectors on the same nanoscale chip [64].

Self-powered UV photodetectors

The goal of semiconductor technology is to build optoelectronic devices with high performance and low power consumption. Therefore, efficient UV photodetectors which operate with low power supply are urgently needed. Unfortunately, to get reasonable detectivity, most of the photodetectors require additional power, which makes the overall circuitry heavy and uneconomical in the current energy scenario. Thus, a new type of UV photodetectors which operate without any power supply, namely self-powered photodetectors, seem to proffer an effective strategy to solve the energy issues, and have been attracting considerable attention [65].

Up to now, many approaches have been developed to fabricate self-powered UV photodetectors. These devices can be divided into two major classes from the viewpoint of energy conversion: one class includes photovoltaic devices containing *p*–*n* junctions, heterojunctions, Schottky junctions, among others, which could transform UV radiation into electrical energy directly by the photovoltaic effect; the other mainly contains photoconductive devices with integrated power sources, which transform UV radiation into electrical energy along with mechanical energy or chemical energy. These devices are usually operated by the conjunct

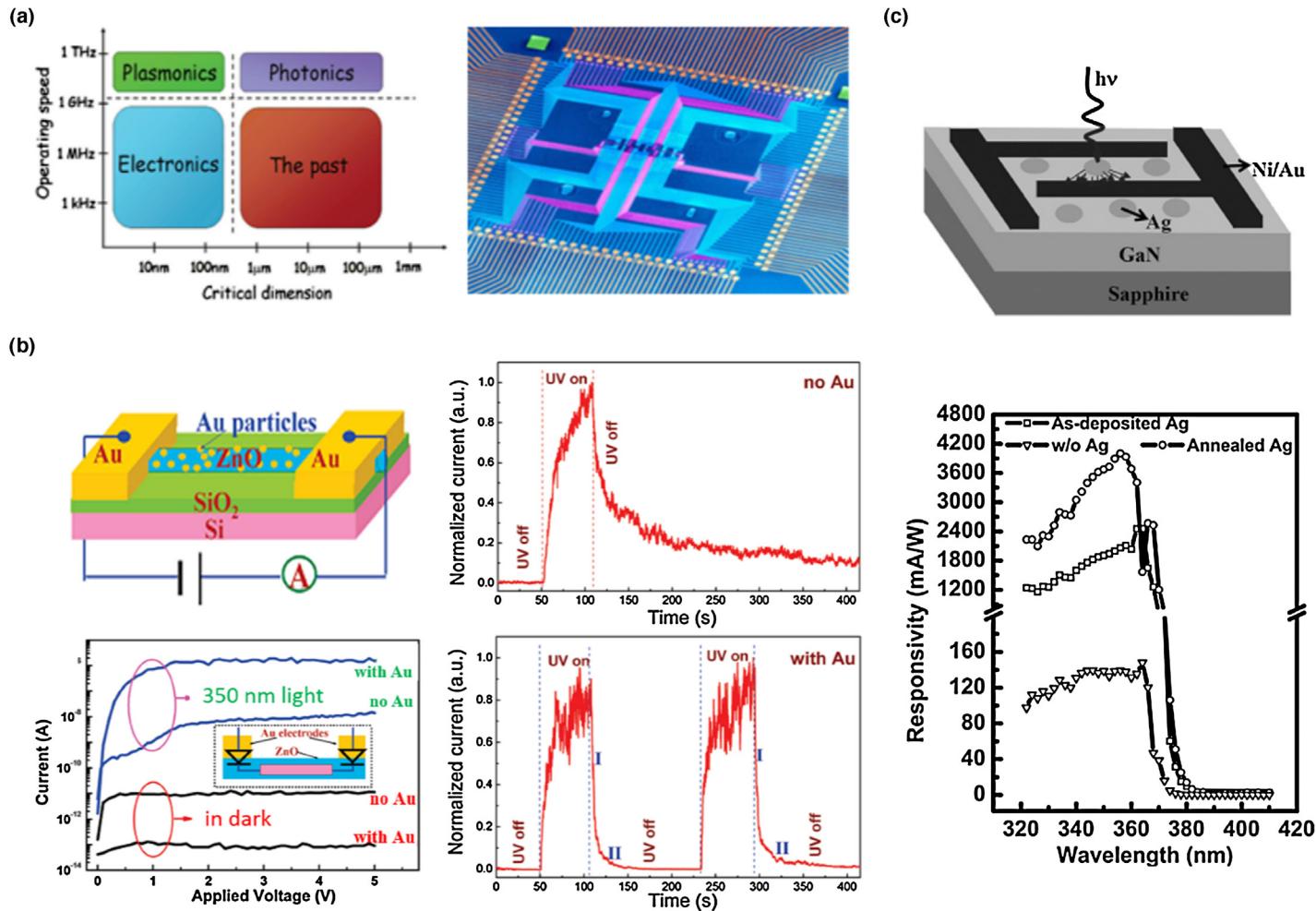


FIGURE 6

Minimization for UV detector by plasmonics. (a) Operation speeds and crucial dimensions of various chip-scale device technologies. Crossbar nanowire chips are combined to form tiny CPU for beyond Moore's-law electronics. Reproduced with permission [42,43]. Copyright © 2006 Elsevier. (b) Giant improvement of the performance of ZnO nanowire photodetectors by Au nanoparticles. Reproduced with permission [47]. Copyright © 2010 American Chemical Society. (c) High-performance GaN UV detector realized by nanoplasmonic enhancement. Reproduced with permission [48]. Copyright © 2012 WILEY-VCH.

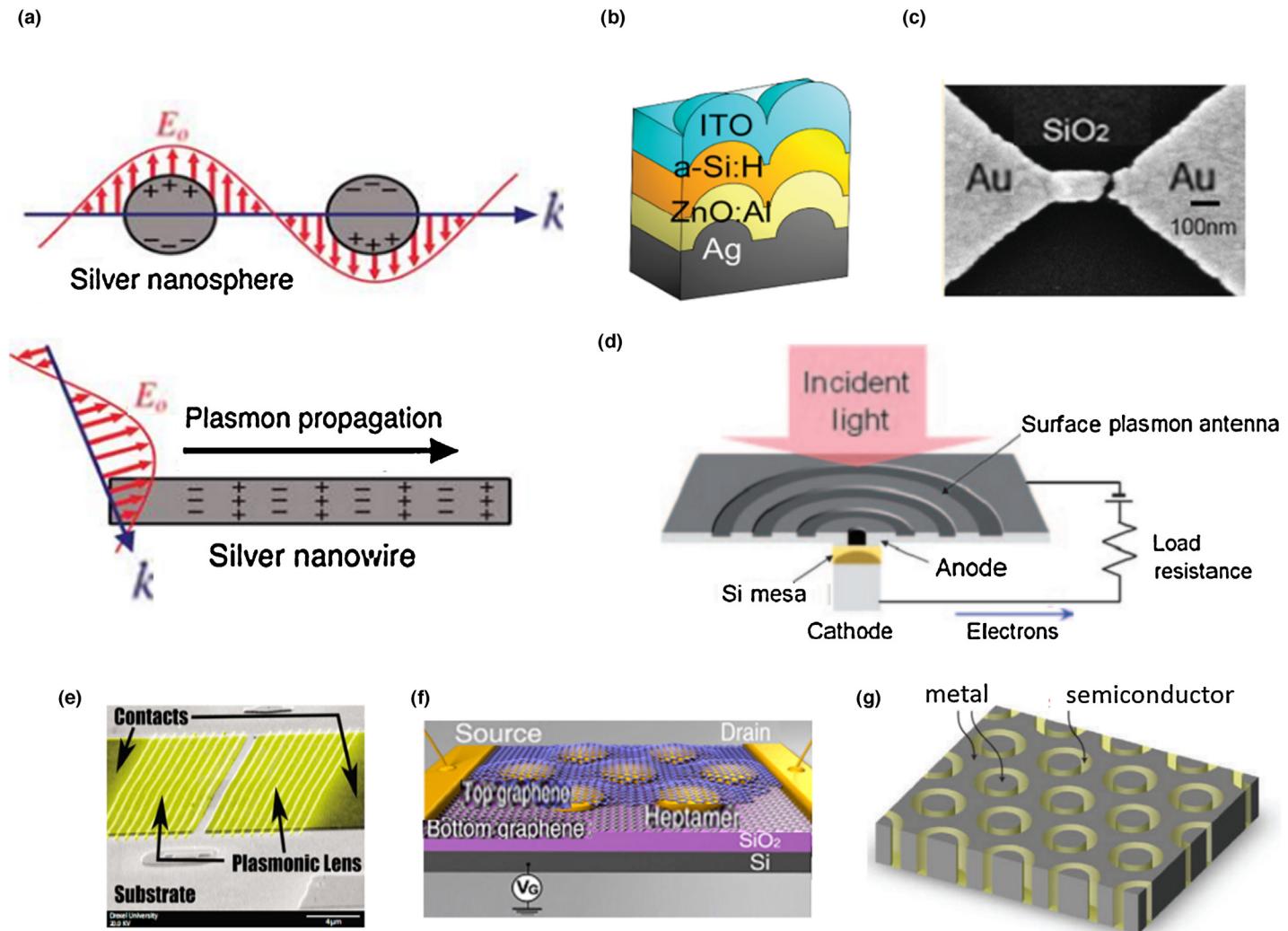
photoelectric effect with the piezoelectric effect, or the photoelectrochemical effect.

Albeit the photovoltaic effect is an ancient concept, it still exhibits huge potential for the fabrication of the novel self-power UV photodetectors with high performance. Figs. 8a–c show examples of self-powered UV photodetectors made from several types of photovoltaic structures. Fig. 8a is a homojunction p -ZnO (Li, N codoping method)/ n -ZnO UV detector, and its photoresponse exhibits little variation at 0 bias voltage during the intermittent measurements for five months [66]. Fig. 8b is another type of self-powered UV photodetectors based on n -ZnO/ p -NiO core–shell heterojunction with a high spectrum-selective feature and high photoresponse speed [67]. And Fig. 8c is a new type of self-powered photodetector based on an asymmetric metal–semiconductor–metal (MSM) structure; in this configuration, it has a higher responsivity and UV/VIS rejection ratio, and much faster photoresponse speed than the conventional photovoltaic photodetectors [68].

Figs. 8d–f show another type of self-powered UV photodetectors with integrated power source. Although the piezoelectric effect or

photoelectrochemical effect extended the photoelectric devices for only a short time, a lot of progress has been made in fabricating self-powered UV photodetector. As shown in Fig. 8d, in conjunction with a fuel cell, which can be used to convert the chemical energy into electricity, the photoelectrochemical system exhibits a considerable photovoltaic effect under UV light irradiance [69]. Similarly, self-powered UV photodetectors based on the photoelectrochemical effect have been realized successfully (Fig. 8e) [70]. Besides, energy harvest of the nanogenerator through the piezoelectric effect exerts control of the electron–hole pair generation, transport and recombination process, enabling the nanogenerator to be a suitable power supply for photodetectors to replace the commonly used external power supply. Fig. 8f shows a UV photodetector powered by its nanogenerator using the piezoelectric effect. As the authors demonstrated, the same system may be integrated into blood vessels and function accordingly, utilizing the vessel's pulse movement [71].

Despite the great progress that has been made in the new field of self-powered UV photodetectors, the scaling of these devices to practical applications requires much more work. For instance,

**FIGURE 7**

Combining photodetectors with plasmonics may enhance photoelectronic conversion efficiency: (a) Schematic illustration of the two types of plasmonic nanostructures: a localized surface plasmon resonance (LSPR) and propagating surface plasmon (PSP). Reproduced with permission [49]. Copyright © 2011 American Chemical Society. (b) Optimized spatial correlations for broadband light trapping nanopatterns in high efficiency ultrathin film a-Si:H solar cells. Reproduced with permission [50]. Copyright © 2011 American Chemical Society. (c) Plasmon resonance in individual nanogap electrodes studied using graphene nanoconstrictions as photodetectors. Reproduced with permission [51]. Copyright © 2011 American Chemical Society. (d) Si nano-photodiode with a surface plasmon antenna. Reproduced with permission [52]. Copyright © 2005 The Japan Society of Applied Physics. (e) Integrated plasmonic lens photodetector. Reproduced with permission [53]. Copyright © 2009 American Institute of Physics. (f) Graphene-antenna sandwich photodetector, Reproduced with permission [54]. Copyright © 2012 American Chemical Society. (g) Array of coaxial holes in a metal film that supports localized Fabry-Perot plasmon modes. Reproduced with permission [55,56]. Copyright © 2010 Macmillan Publishers Limited.

innovative approaches should be developed to enhance the spectral responsivity, reduce its dark current, speed up the response time, as well as scale down the size and weight of devices, especially that of the additional energy harvesting system.

Portable UV photodetectors based on flexible electronics

Recently, flexible electronics has been flourished to the point of developing portable, wearable, lightweight and implantable optoelectronic devices [72]. It also offers numerous opportunities for the development of next-generation UV photodetectors. Up to now, research on flexible UV detectors has been carried out in many groups. Fig. 9 illustrates several representative devices. A flexible SnO₂ photodetector using carbon cloths as the templates is

shown in Fig. 9a. Self-powered by the flexible battery, the current-time curves of the device (red line) is comparable to a common photodetector device driven by an external power source (blue line), and the extent of bending has little influence on the performance of the integrated device [73]. Similarly, flexible devices can also be fabricated by printing ZnO nanowells and metal electrodes onto polyimide substrates (Fig. 9b), and the $I-V$ curves of this device are almost identical for different bending curvatures as well [74]. Moreover, researchers have found that flexible devices can also be compatible with various types of substrates, even including plastics, paper, textiles and curved/bio-surfaces. Fig. 9c exhibits that the devices formed on tree leaves can work as high-performance UV photodetectors with great reliability even after being bent to a small radius of 2 mm [75]. More interestingly is the

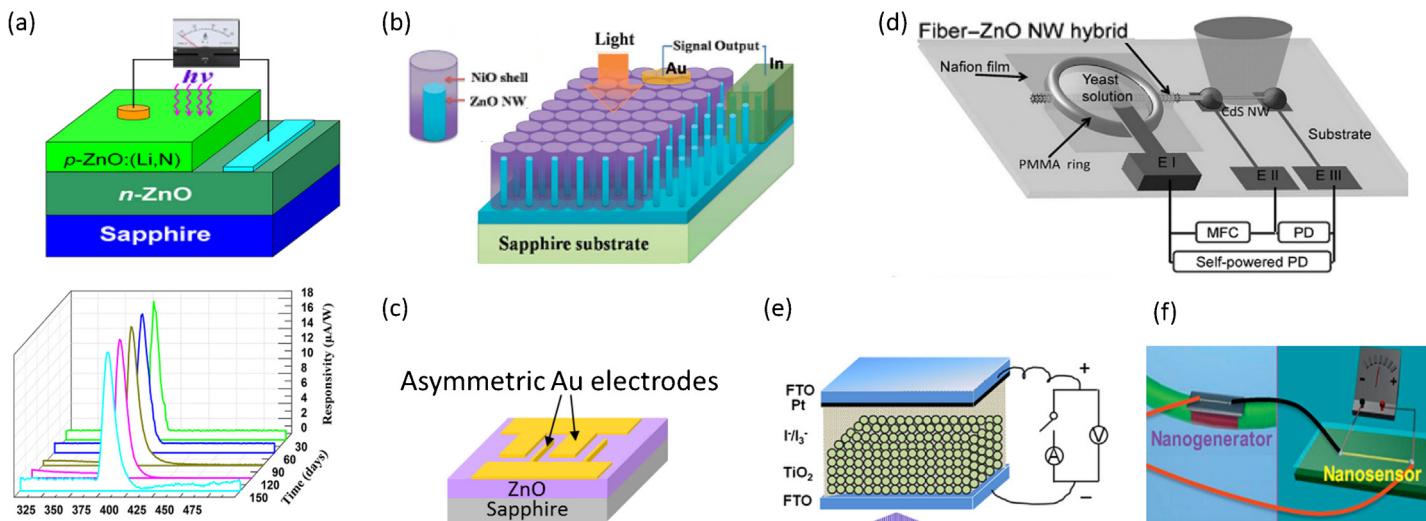


FIGURE 8

Self-powered UV photodetectors with different working mechanisms: (a–c) Photovoltaic effect, (d–f) photoelectrochemical effect, photoelectric effect and piezoelectric effect, respectively. (a) Photovoltaic effect resulting from ZnO homo-junction. Reproduced with permission [66]. Copyright © 2013 American Institute of Physics. (b) Photovoltaic effect ZnO/NiO core/shell hetero-junction. Reproduced with permission [67]. Copyright © 2013 Royal Society of Chemistry. (c) Schottky barrier diode formed by an asymmetry MSM structure. Reproduced with permission [68]. Copyright © 2014 Royal Society of Chemistry. (d) UV sensors cooperate with a hybridized microbial fuel cell. Reproduced with permission [69]. Copyright © 2012 Elsevier Ltd. (e) UV sensors driven by a photoelectrochemical cell. Reproduced with permission [70]. Copyright © 2012 Elsevier. (f) Using a nanogenerator to harvest energy of the pulse movement of the pressure pipe to power a nano-scaled UV sensor. Reproduced with permission [71]. Copyright © 2012 Elsevier Ltd.

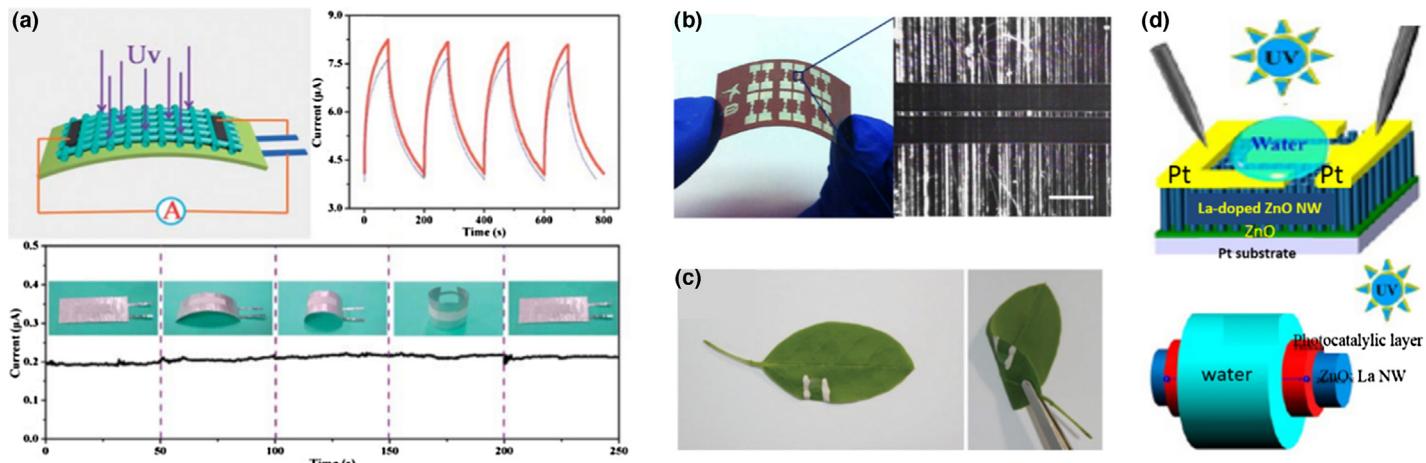


FIGURE 9

Flexible UV photodetectors. (a) A self-powered and fully flexible photodetector nanosystem fabricated with SnO₂-microtube-assembled cloths. The current-time curves of the self-powered photodetector device (red line) is comparable to a common photodetector device driven by an external power source (blue line), and the extent of bending has little influence on the performance of the integrated device. Reproduced with permission [73]. Copyright © 2013 Royal Society of Chemistry. (b) An all-printable flexible ZnO nanowire photodetector, scale bar is 30 μm . Reproduced with permission [74]. Copyright © 2014 Macmillan Publishers Limited. (c) Flexible and transparent SnO₂ nanobelts UV photodetectors built on tree leaves. Reproduced with permission [75]. Copyright © 2014 Nature Publishing Group. (d) Water and humidity enhanced UV detector by using p-type La-doped ZnO nanowires on a flexible polyimide substrate. Reproduced with permission [76]. Copyright © 2013 American Chemical Society.

flexible UV detector in Fig. 9d, the La-doped ZnO nanowires grown on a flexible polyimide substrate, where performance could be enhanced significantly by increasing ambient humidity [76].

The above results indicate the great application potential of wide band-gap semiconductor nanomaterials as flexible UV detectors, although the aforementioned techniques used for the fabrication of soft devices are still premature for industrial implementation. Work to improve the sensitivity of flexible devices has

been carried out in some groups. It is believed that the continuous improvement of fabrication techniques could bring the portable and wearable ‘roll up’ UV photodetectors out of lab in the near future.

Conclusions and outlook

Obviously, the newly developed materials, the improved fabrication techniques and the nano-invention provide a huge

TABLE 1**Materials candidates for fabricating UV detectors with different band-gap [12,21,25–31,34–37,77–90].**

		Visible-blind					
10 nm	200 nm	280 nm	320 nm	400 nm			
		Solar-blind					
UVC		UVB (eV) 3.88 ≤ E _g < 4.43		UVA (eV) 3.10 ≤ E _g < 3.88		Visible & IR (eV) E _g < 3.10	
VUV (eV) 6.20 ≤ E _g < 12.4	DUV (eV) 4.43 ≤ E _g < 6.20						
MgF ₂	10.8	HfO ₂	5.93	----	----	ZnS	3.70
BeO	10.6	GeO ₂	5.60	----	----	NiO	3.70
GaF ₂	10.0	LaAlO ₃	5.60	----	----	In ₂ O ₃	direct 3.60
SiO ₂	9.00	diamond	5.50	----	----	Zn ₂ SnO ₄	3.60
ZrO ₂	7.80	α-Si ₃ N ₄	5.10	----	----	SnO ₂	3.60
MgO	7.78	β-Ga ₂ O ₃	4.90	----	----	Nb ₂ O ₅	3.40
Al ₂ O ₃	6.95	Yb ₂ O ₃	4.90	----	----	GaN	3.39
AlN	6.20	Nd ₂ O ₃	4.70	----	----	ZnO	3.37
----	----	Zn ₂ GeO ₄	4.68	----	----	WO ₃	3.25 (2.70)
----	----	Ta ₂ O ₅	4.65	----	----	CeO ₂	3.20
----	----	MgS	4.45	----	----	4H-SiC	3.20
----	----	In ₂ Ge ₂ O ₇	4.43	----	----	TiO ₂	3.20
(semiconductor alloy)						MoS ₂	Single layer 1.80
MgNiO / MgZnO / BeMgZnO / MgZnS / AlGaN / ZrTiO ₂ / InGaZnO						Bulk 1.60	
						GaAs	1.43
						Si	1.12

opportunity for the development of new-generation UV detectors. However, a revolutionary design concept is further needed to explore versatile photodetectors toward the intelligent era beyond Moore's-law. Therefore, for the study of new concept UV photodetectors in the future, efforts should be made in the following three priority areas: materials, architectures and applications. Firstly, exploring suitable materials as an active layer is one of the fundamental driving forces for developing novel UV detectors. Table 1 summarizes selected candidate materials with band-gap ranging from the VUV to IR regime. Although semiconductors with a band-gap in the solar UVB regime (which has a wide range of harmful effects [4]) are scarce, UVB photodetectors have been explored by the alloy semiconductor fabrication techniques, and the detection and quantification of UV radiation at any wavelength can be realized nowadays [14,38,83,85–89].

However, the successful utilization of band-gap engineering has mainly benefited from sophisticated fabrication technologies such as MBE and MOCVD (Fig. 3). Therefore, to explore the diversity of materials for advanced UV photodetectors, the controlled growth and assembly of nanostructures using energy band-gap engineering with low cost should be developed. Secondly, on the basis of manipulating and processing materials at the nanoscale with reliable reproducibility, plasmonic technology and energy band-gap engineering shall be used to fabricate various functional units (e.g. superlattice photoconductors), and further to that, advanced devices which could detect weak optical signals precisely at very high speed (e.g. germanium avalanche UV nano-photodetectors, tunneling devices, bipolar transistors, among others). Thirdly, from a practical perspective, self-powered UV photodetectors on flexible chips with multifunctions have great potential to become commonly applied devices, because they can not only be used as special 'electronic noses' to detect the humidity, toxic gas sensitivity while being powered by themselves, but also function as flexible batteries, or hybrid supercapacitors.

Therefore, there is still plenty of room for the design of regenerative UV detectors in this flourishing age of optoelectronics. It is

believed that future work in the field should continue to be focused on generating semiconductor nanostructures in a more controlled, predictable and simpler way. Moreover, smart, intelligent, portable and multifunctional design concepts will bring more types of UV photodetectors out of the lab and help make them ready for real applications.

Acknowledgements

The authors would like to thank Dr Nan Gao, Dr Xiaojie Xu and Dr Xiuhua Xie for their kind helps. This work is supported by the National Natural Science Foundation of China (Grant Nos. 51471051, 51372040, 61376054, 61475153 and 11404328), the National Basic Research Program of China (973 program) (No. 2011CB302006), the 100 Talents Program of the Chinese Academy of Sciences, Science and Technology Commission of Shanghai Municipality (13NM1400300) and Shanghai Shu Guang Project (12SG01).

References

- [1] P.E. Glaser, *Science* 162 (1968) 857–861.
- [2] <http://en.wikipedia.org/wiki/Sunlight#>.
- [3] A.F. McKinlay, et al. *Health Phys.* 87 (2) (2004) 171–186.
- [4] S.D.A.M. Stephen De Mora, Enhanced UV radiation - a new problem for the marine environment. vol. 10, Cambridge University Press, 2000, pp. 1–34.
- [5] S.E. Mancebo, et al. *Rev. Environ. Health* 29 (3) (2014) 265–273.
- [6] B. Leckner, *Sol. Energy* 20 (1977) 143–150.
- [7] L. Peng, et al. *Adv. Mater.* 25 (37) (2013) 5321–5328.
- [8] G. Konstantatos, et al. *Nat. Nanotechnol.* 5 (6) (2010) 391–400.
- [9] M. Razeghi, et al. *J. Appl. Phys.* 79 (10) (1996) 7433.
- [10] E. Monroy, et al. *Semicond. Sci. Technol.* 18 (4) (2003) R33–R51.
- [11] K. Liu, et al. *Sensors* 10 (9) (2010) 8604–8634.
- [12] Y.K. Fang, et al. *IEEE Trans. Electron Devices* 39 (2) (1992) 292–296.
- [13] X.H. Xie, et al. *Appl. Phys. Lett.* 101 (8) (2012) 81104.
- [14] H. Zhu, et al. *J. Phys. Chem. C* 112 (51) (2008) 20546–20548.
- [15] M. Liao, et al. *Appl. Phys. Lett.* 90 (12) (2007) 123507.
- [16] R. McClintock, et al. *Appl. Phys. Lett.* 87 (24) (2005) 241123.
- [17] P. Yang, et al. *Nano Lett.* 10 (5) (2010) 1529–1536.
- [18] Y. Zhao, et al. *Sci. Rep.* 4 (2014) 6847.
- [19] X. Xu, et al. *Adv. Funct. Mater.* 25 (3) (2015) 445–454.
- [20] D. Ick Son, et al. *Appl. Phys. Lett.* 102 (2) (2013) 21105.
- [21] X. Fang, et al. *Adv. Mater.* 21 (20) (2009) 2034–2039.
- [22] X. Wang, et al. *Chem. Soc. Rev.* 43 (5) (2014) 1400–1422.
- [23] X. Fang, et al. *Adv. Funct. Mater.* 20 (3) (2010) 500–508.
- [24] L. Hu, et al. *Adv. Mater.* 24 (17) (2012) 2305–2309.
- [25] F. Wang, et al. *Nanoscale* 5 (7) (2013) 2864.
- [26] H. Chen, et al. *Adv. Funct. Mater.* 22 (6) (2012) 1229–1235.
- [27] X. Fang, et al. *Adv. Mater.* 21 (48) (2009) 5016–5021.
- [28] L. Hu, et al. *Adv. Mater.* 23 (17) (2011) 1988–1992.
- [29] Y. Xie, et al. *Nanotechnology* 25 (7) (2014) 75202.
- [30] X. Fang, et al. *Adv. Funct. Mater.* 21 (20) (2011) 3907–3915.
- [31] H. Liu, et al. *Adv. Opt. Mater.* 2 (8) (2014) 771–778.
- [32] L. Hu, et al. *Adv. Mater.* 24 (43) (2012) 5872–5877.
- [33] L. Hu, et al. *Small* 7 (8) (2011) 1012–1017.
- [34] C. Yan, et al. *Appl. Phys. Lett.* 96 (5) (2010) 53108.
- [35] D. Tsai, et al. *ACS Nano* 7 (5) (2013) 3905–3911.
- [36] R. Zou, et al. *Small* 10 (9) (2014) 1848–1856.
- [37] Z. Wang, et al. *Nano Lett.* 12 (9) (2012) 4715–4721.
- [38] Z. Guo, et al. *Appl. Phys. Lett.* 93 (16) (2008) 163501.
- [39] L. Sang, et al. *Sci. Rep.* 3 (2013) 2368.
- [40] X. Wang, et al. *Nanoscale* 6 (20) (2014) 12009–12017.
- [41] V.J. Sorger, et al. *MRS Bull.* 37 (8) (2012) 728–738.
- [42] <http://www.extremetech.com/computing/175874-crossbar-nanowire-chips-combine-to-form-tiny-cpu-for-beyond-moores-law-electronics>.
- [43] R. Zia, et al. *Mater. Today* 9 (7/8) (2006) 20–27.
- [44] X. Fan, et al. *Light: Sci. Appl.* 3 (6) (2014) e179.
- [45] C. Fei Guo, et al. *Light: Sci. Appl.* 3 (4) (2014) e161.
- [46] J.A. Schuller, et al. *Nat. Mater.* 9 (3) (2010) 193–204.

- [47] K. Liu, et al. *J. Phys. Chem. C* 114 (46) (2010) 19835–19839.
- [48] D. Li, et al. *Adv. Mater.* 24 (6) (2012) 845–849.
- [49] M. Rycenga, et al. *Chem. Rev.* 111 (6) (2011) 3669–3712.
- [50] V.E. Ferry, et al. *Nano Lett.* 11 (10) (2011) 4239–4245.
- [51] S.F. Shi, et al. *Nano Lett.* 11 (4) (2011) 1814–1818.
- [52] I.S.H.I. Tsutomu, et al. *Jpn. J. Appl. Phys.* 44 (2005) 364–366.
- [53] J.A. Shackleford, et al. *Appl. Phys. Lett.* 94 (8) (2009) 83501.
- [54] Z. Fang, et al. *Nano Lett.* 12 (7) (2012) 3808–3813.
- [55] H.A. Atwater, et al. *Nat. Mater.* 9 (3) (2010) 205–213.
- [56] R. de Waele, et al. *Nano Lett.* 9 (8) (2009) 2832–2837.
- [57] M. Jiang, et al. *J. Mater. Chem. C* 2 (1) (2013) 56.
- [58] Y. Lai, et al. *Light: Sci. Appl.* 2 (6) (2013) e76.
- [59] H. Chen, et al. *Appl. Phys. Lett.* 104 (9) (2014) 91119.
- [60] H. Chen, et al. *J. Phys. Chem. C* 118 (1) (2014) 679–684.
- [61] B.J. Lawrie, et al. *Nano Lett.* 12 (12) (2012) 6152–6157.
- [62] J.B. Lassiter, et al. *Nano Lett.* 12 (2) (2012) 1058–1062.
- [63] J. Ye, et al. *Nano Lett.* 12 (3) (2012) 1660–1667.
- [64] S.A. Maier, *Nat. Mater.* 8 (9) (2009) 699–700.
- [65] Z.L. Wang, *Adv. Mater.* 24 (2) (2012) 280–285.
- [66] H. Shen, et al. *Appl. Phys. Lett.* 103 (23) (2013) 232112.
- [67] P. Ni, et al. *J. Mater. Chem. C* 1 (29) (2013) 4445.
- [68] H. Chen, et al. *J. Mater. Chem. C* 2 (45) (2014) 9689–9694.
- [69] Q. Yang, et al. *Angew. Chem. Int. Ed.* 51 (26) (2012) 6443–6446.
- [70] X. Li, et al. *Nano Energy* 1 (4) (2012) 640–645.
- [71] S. Bai, et al. *Nano Energy* 1 (6) (2012) 789–795.
- [72] M. Segev-Bar, et al. *ACS Nano* 7 (10) (2013) 8366–8378.
- [73] X. Hou, et al. *Nanoscale* 5 (17) (2013) 7831.
- [74] X. Liu, et al. *Nat. Commun.* 5 (2014).
- [75] S. Huang, et al. *NPG Asia Mater.* 6 (2) (2014) e86.
- [76] C. Hsu, et al. *ACS Appl. Mater. Interfaces* 5 (21) (2013) 11142–11151.
- [77] Y. Xu, et al. *Am. Mineral.* 85 (3/4) (2000) 543.
- [78] K.F. Mak, et al. *Phys. Rev. Lett.* 105 (13) (2010).
- [79] P. Broqvist, et al. *Appl. Phys. Lett.* 94 (14) (2009) 141911.
- [80] Z. Yu, et al. *Chin. Phys. Lett.* 30 (6) (2013) 67801.
- [81] P. Wu, et al. *J. Mater. Chem.* 21 (8) (2011) 2563.
- [82] H.L. Liang, et al. *Appl. Phys. Lett.* 98 (22) (2011) 221902.
- [83] Z.G. Ju, et al. *Appl. Phys. Lett.* 93 (17) (2008) 173505.
- [84] Q. Zheng, et al. *Appl. Phys. Lett.* 98 (22) (2011) 221112.
- [85] M. Fan, et al. *J. Mater. Chem. C* 3 (2) (2015) 313–317.
- [86] L.K. Wang, et al. *Appl. Phys. Lett.* 95 (13) (2009) 131113.
- [87] K. Huang, et al. *Nano Res.* 3 (4) (2010) 281–287.
- [88] H. Zhang, et al. *IEEE Electron Device Lett.* 32 (5) (2011) 653–655.
- [89] W. Tian, et al. *Nanoscale* 4 (20) (2012) 6318.
- [90] L.W. Lu, et al. *J. Cryst. Growth* 265 (1/2) (2004) 28–33.