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Upconversion nanoparticles extending the spectral sensitivity of silicon photodetectors to $\lambda = 1.5\ \mu\text{m}$

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Abstract

The telecommunication wavelength of $\lambda = 1.5\ \mu\text{m}$ has been playing an important role in various fields. In particular, performing photodetection at this wavelength is challenging, demanding more performance stability and lower manufacturing cost. In this work, by integrating solution-processed Er^{3+} doped NaYF_4 upconversion nanoparticles (UCNPs) onto a silicon photodetector, UCNPs/Si hybrid photodetectors (hybrid PDs) are presented. Upon optimization, we demonstrated that a layer of UCNPs can well lead to an effective spectral sensitivity extension without scarification of the photodetection performance of the Si photodetector in the visible and near-infrared (near-IR) spectrum. Under the $\lambda = 1.5\ \mu\text{m}$ illumination, the hybrid UCNPs/Si-PD exhibits a room-temperature detectivity of 6.15×10^{12} Jones and a response speed of 0.4 ms. These UCNPs/Si-PDs represent a promising hybrid strategy towards the quest of low-cost and broad-band photodetection sensitive from the visible down to the short-wave infrared spectrum.

Keywords: photodetectors, upconversion nanoparticles, short-wave infrared, solution-process

1. Introduction

Light sources and photodetection elements operating at a wavelength (λ) of 1.5 μm have been playing a critical role in various fields, such as optoelectronics [1–3], telecommunications [4], and passive night vision [5]. At $\lambda = 1.5 \mu\text{m}$, the optical loss is lowest in a typical silica fiber, resulting in the wide application of this wavelength in optical communications [6]. This wavelength is also chosen to enable better-performing light detection and ranging [7, 8] due to its eye-safe characteristics, allowing a larger detection range than devices applying illumination in the visible or near-IR spectra [9]. Current photodetector technologies for $\lambda = 1.5 \mu\text{m}$ mainly rely on low-bandgap inorganic semiconductors [10], such as indium gallium arsenide (InGaAs), lead sulfide (PbS), germanium (Ge), indium antimonide (InSb) and mercury cadmium telluride (HgCdTe). Many of these photodetectors are required to function at low temperatures. In addition, their fabrication often involves epitaxial growth and highly toxic elements (e.g. arsenic, lead, mercury, cadmium, and tellurium), causing both cost and ecological issues. In the research into alternative or next-generation photodetection technologies sensitive to $\lambda = 1.5 \mu\text{m}$, various new materials have emerged including graphene [11–13], MoS₂ [14], black phosphorus [15, 16], colloidal PbS nanocrystals [17, 18], plasmonic nanostructures generating hot carriers [19–21], and colloidal plasmonic nanoparticles exhibiting strong photothermal effects [20, 21]. Nevertheless, many of these do not completely resolve both the cost issue due to the highly rigorous nanofabrication processes required (and the low yield of reproducibility) and the ecological challenges due to the application of highly toxic elements such as lead.

Recently, photon upconversion, the process of converting low-energy photons to high-energy ones, has been applied as another strategy in pursuit of low-cost alternative photodetection at $\lambda = 1.5 \mu\text{m}$. For example, Zhang et al recently fabricated hybrid photoconductors sensitive to $\lambda = 1.5 \mu\text{m}$ using organo-lead hybrid perovskites deposited on top of an erbium silicate nanosheet, resulting in a photoresponsivity of 0.1 mA W⁻¹ and a rise time of about 900 μs [22]. Solution-processed colloidal upconversion nanoparticles (UCNPs), typically doped by trivalent lanthanide cations, have also shown their high potential for such applications. Besides the fields of biomedical engineering [23–25] and solar energy harvesting [26, 27], they have also been applied to photodetection [28, 29]. Working on photodetectors sensitive to the wavelength of 1.5 μm , Zhao and co-workers recently fabricated flexible photoconductors by mixing Er³⁺-doped UCNPs with conjugated polymer [28]. Despite the interesting demonstration, the response speed of these photoconductors was not well characterized. By using a photodiode structure, we have recently demonstrated solution-processed flexible polymer/UCNP hybrid photodetectors exhibiting a responsivity of 0.73 mA W⁻¹ and a rise time of 80 μs [29]. In these conjugated polymer/UCNP hybrid

photodetectors, while the inorganic UCNP are highly stable in air, the air stability of the conjugated polymer remains modest. By comparison, an all-inorganic configuration should in principle exhibit advantages. In this work, we propose an all-inorganic hybrid photodetector (hybrid PD) sensitive to $\lambda = 1.5 \mu\text{m}$ employing a layer of solution-processed colloidal Er^{3+} -doped NaYF_4 UCNP on a silicon photodetector. In such a configuration, the UCNP absorb $\lambda = 1.5 \mu\text{m}$ photons and upconvert them into fluorescence falling in the visible and the near-IR spectrum (at $\lambda = 520 \text{ nm}$, 545 nm , 650 nm , 810 nm , and 980 nm), which is subsequently harvested by the Si photodetector resulting in photocurrent generation. In an optimized UCNP/Si hybrid PD, a high photoresponsivity of more than 10 mA W^{-1} and a room-temperature detectivity of 6.15×10^{12} Jones, together with a rise time as low as $430 \mu\text{s}$ were achieved under $\lambda = 1.5 \mu\text{m}$ illumination. The results reported here represent a more than ten-fold enhancement in terms of photoresponsivity by comparison to previous works applying Er^{3+} -doped upconversion materials on hybrid lead perovskites [22] or on conjugated polymers [29]. The room-temperature detectivity of 6.15×10^{12} Jones obtained by the work under $\lambda = 1.5 \mu\text{m}$ illumination suggests a strong competitiveness of these UCNP/Si hybrid PDs by comparison to commercial PDs sensitive at this wavelength [10]. The current UCNP/Si hybrid PDs described here thus pave a new path towards low-cost and broadband photodetection sensitive in the spectrum from visible light down to the short-wave infrared.

2. Experimental section

2.1. Synthesis method of Er^{3+} -doped NaYF_4 UCNP

A hydrothermal route [29, 30] was used for the synthesis of the Er^{3+} -doped NaYF_4 UCNP in this work. Firstly, three aqueous solutions were prepared by adding $\text{Ln}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (0.2 mol l^{-1}), sodium citrate tribasic dihydrate (0.6 mol l^{-1}), and sodium fluoride (NaF , 2.4 mol l^{-1}) to 5 ml of deionized (DI) water, named solution A, solution B and solution C, respectively. For solution A, the Ln^{3+} contained Y^{3+} and Er^{3+} with a $\text{Y}^{3+}/\text{Er}^{3+}$ molar ratio of 85:15. Solutions A and B were then mixed together with vigorous stirring to form a lanthanide citrate. Solution C was subsequently slowly added into the above mixture and the final solution was stirred for 1 h. Afterwards, this final solution was transferred into an autoclave for hydrothermal treatment in an oven at 120°C for a duration of 2 h. The autoclave was then taken out of the oven and allowed to cool to room temperature naturally (overnight). A centrifugation (6000 rpm, 30 min) process was used to separate the UCNP from the solution. The UCNP were then washed several times in DI water. Finally, the UCNP were dried in a vacuum (60°C , 24 h) and subsequently annealed in air (300°C , 2 h).

2.2. Device preparation and characterization

A Si PD (LSSPD-1.2) was obtained from Beijing Lightsensing Technologies Ltd (a 1.2 mm Silicon PIN photodiode, size: 1.2 mm $\times$ 1.2 mm). The UCNPs were firstly dispersed in isopropanol (IPA) by ultrasonication. The concentrations for UCNPs-1, UCNPs-2 and UCNPs-3 were 20 g l⁻¹, 30 g l⁻¹ and 40 g l⁻¹, respectively. To prepare the UCNP/Si PDs, 60 μ l of UCNP solution was drop-coated onto the surface of the Si photodetector. For photoresponsivity measurement in the λ = 350 nm–1650 nm spectrum window, monochromatic light was generated by a tungsten halogen lamp coupled with a monochromator (Oriel Cornerstone 130); the emission characteristic of the tungsten halogen lamp is shown in figure S1 of the supplementary material. This monochromatic light was then modulated by a mechanical chopper (SR540, Stanford Research Systems. Inc.) with its modulation frequency adjustable from 4 Hz to 3.7 kHz. During our experiments, a modulation frequency of 17 Hz was applied, with the chopper placed between the light source and the photodetector under study. The short-circuit current of the photodetector was measured by a computer-controlled Keithley 2612B SourceMeter® instrument (with an applied voltage of 0 V). NIST-calibrated Si and Ge cells were used as references to calibrate the monochromatic illumination power at every wavelength. For the power-dependent and time-dependent photoresponse characteristics, the hybrid PDs were illuminated by a laser at λ = of 1.5 μ m, modulated by a function generator. The photocurrent was converted by a low-noise current preamplifier (SR570) into a voltage signal which was monitored by a digital oscilloscope (Tektronix DPO2024B). All device measurements were performed in air at room temperature.

2.3. Material characterizations

SEM images of the UCNPs were obtained by a FEI Magellan 400 system with a standard field emission gun source. Powder x-ray powder diffraction (XRD) spectra were obtained by a PANalytical X'Pert x-ray diffractometer using Cu-K α radiation. The optical absorption was measured in air by an Agilent Cary 5E UV–vis/near-IR spectrometer. The steady-state fluorescence of the UCNPs was recorded by an Ocean Optics spectrometer (HR4000) while the sample (UCNPs) was excited by a laser diode (LPSC-1550-FC, center wavelength: 1537 nm). For time-resolved fluorescence, the UCNPs were first deposited onto a microscopy glass slide. The fluorescence was recorded using a tunable optical parametric oscillator pumped by a tunable Ekspla S-7NT342B OPO laser with a 7 ns pulse duration at 1540 nm. A CCD camera (Princeton Instruments) equipped with a monochromator (Acton Research, 300 lines mm⁻¹) was used to measure the fluorescence spectra. An RCA 8850 photomultiplier was used to detect the decay curves. All measurements were performed at room temperature.

3. Results and discussion

Figure 1. (a) Transmission electron microscopy (TEM) image of Er^{3+} -doped NaYF_4 UCNPs. (b) X-ray powder diffraction (XRD) pattern of the UCNPs plotted together with the reference pattern (JCPDS no. 00-016-0334). (c) The upconversion fluorescence spectrum of the UCNPs (the red dotted curve) under a laser excitation at $\lambda = 1.5 \mu\text{m}$ (power = 10 mW). The absorbance spectra of Si is shown as the black curve. (d) Schematic illustrating the energy transitions corresponding to the upconversion fluorescence observed under the excitation of a $\lambda = 1.5 \mu\text{m}$ laser. GSA = ground-state absorption, ESA = excited-state absorption.

The solution-processed colloidal Er^{3+} -doped NaYF_4 UCNPs were synthesized by a hydrothermal method according to a previously described protocol [29, 30]. The UCNPs applied in this work have an average diameter of 450 nm (Figure 1(a)). A hexagonal β phase, a crystal structure which generally allows for a stronger fluorescence than the cubic phase [31], was determined by XRD to be present in these UCNPs (Figure 1(b)). When Er^{3+} -doped NaYF_4 UCNPs are excited by a $\lambda = 1.5 \mu\text{m}$ laser, the incident photons are absorbed by the Er^{3+} cation, either through ground-state absorption or excitedstate absorption (see the schematic shown in Figure 1(d)). The upconversion process, which converts lower-energy incoming photons into higher-energy outgoing photons by fluorescence, typically involves a multiphoton absorption mechanism followed by relaxation, de-excitation, and emission [32, 33]. For example, the fluorescence emissions of Er^{3+} -doped NaYF_4 UCNPs at $\lambda = 520 \text{ nm}$, 545 nm and 650 nm require a three-photon absorption process, while the fluorescence at $\lambda = 810 \text{ nm}$ and 980 nm involves a two-photon absorption process. Even with laser excitation at a relatively low power (10 mW), a bright greenish fluorescence can be observed by the naked eye, as shown in the inset picture in Figure 1(c). By a reported method employing an integrating sphere [34], a fluorescence quantum yield of about 2.5% was determined to have been

achieved by these UCNPs. As the absorption spectrum of Si easily covers all the upconverted fluorescence (the black curve in Figure 1(c)), these results suggest that the UCNPs described here can effectively upconvert $\lambda = 1.5 \mu\text{m}$ photons into fluorescence harvestable by Si.

Figure 2. (a) Schematic describing the device architecture of the UCNPs/Si hybrid PD. (b) Scanning electron microscope (SEM) image of the UCNPs layer of an optimized hybrid PD. The zoom-in SEM image of this layer is shown on the right. (c) A picture of the hybrid PD under the illumination of a $\lambda = 1.5 \mu\text{m}$ laser.

UCNPs were then dispersed in isopropanol giving a concentration ranging from 20 to 40 mg ml^{-1} . These UCNPs solutions were then drop-cast onto the surface of a commercial Si photodetector (Beijing Lightsensing Technologies Ltd, LSSPD-1.2, size: 1.2 mm by 1.2 mm). The resultant UCNPs film thickness was tunable by varying the concentration of the solution. A schematic of these UCNPs/Si hybrid PDs is shown in Figure 2(a). UCNPs layers of different thickness were loaded on the Si photodetector with the majority of the nanoparticle layer corresponding to zero to two monolayers with visible empty areas, or one to two monolayers, or more than two monolayers, which will be referred to below as UCNPs-1, UCNPs-2 and UCNPs-3, respectively. In an optimized hybrid device, the UCNPs form a relatively homogenous layer, with a thickness of less than 2 layers of nanoparticles (UCNPs-2, Figure 2(b)). SEM images of UCNPs-1 and UCNPs-3 are shown in Figure S2 of the supplementary material), covering the Si photodetector and performing upconversion of $\lambda = 1.5 \mu\text{m}$ photons to photons harvestable by Si. To verify the uniformity of the UCNPs film and its influence on photodetection, a smaller laser spot (~ 0.4 mm in diameter) was focused onto different areas of the UCNPs/Si hybrid PD surface, which is shown in

Figure S3 of the supplementary material. Three measurements were performed under identical illumination in each sample area and the results showed only a small photocurrent fluctuation ($< \pm 10\%$) owing to the inhomogeneity of the UCNF film (Figure S3 of supplementary material). In addition, as such a UCNF film has little impact on the visible light transmittance of the Si device underneath (Figure 2(c) and Figure S4 of the supplementary material), the hybrid device was able to retain an almost identical photodetection capability for visible and near-IR photons by comparison with a bare Si photodetector (without the UCNF layer), enabling a broadband photodetection characteristic for the hybrid detector.

Figure 3. Photoresponsivity as a function of incident wavelengths from 400 nm to 1650 nm. The insert figure shows the zoom-in responsivity in the wavelength range from 400 nm to 1200 nm.

The photoresponsivities of these UCNF/Si hybrid PDs as a function of incident photon wavelengths from 350 nm to 1650 nm were characterized under monochromatic illumination obtained from a quartz tungsten halogen light source coupled with a monochromator (Figure 3). Concerning the visible/near-IR spectrum (400–1100 nm), including the bare Si photodetector without any UCNFs (called ‘blank Si-PD’), all devices tested showed a clear photoresponse. Loading a significant amount of UCNFs in this hybrid device configuration (e.g. UCNPs-3) can result in a negative impact on the photodetection capability of the Si device in the visible/near-IR spectrum due to the optical absorption of UCNFs. Nevertheless, as shown in the insert of Figure 3, when a moderate amount of UCNFs were applied (e.g. UCNPs-1 and UCNPs-2 configurations), only a slight decrease ($< 3\%$ @ 950 nm) of photoresponsivity in the visible/near-IR spectrum was found in the hybrid devices by comparison to the blank Si-PD. Concerning photons with a wavelength longer than 1100 nm, as expected from the bandgap of Si, the photoresponsivity of the blank Si-PD starts to drop drastically reaching $\sim 3 \times 10^{-5} \text{ A W}^{-1}$ at $\lambda > 1200 \text{ nm}$. By comparison, in the spectrum window $1400 \text{ nm} < \lambda < 1700 \text{ nm}$, UCNF/Si hybrid PDs exhibited a much higher photoresponsivity, reaching a maximum of 0.008 A W^{-1} at $\lambda = 1.55 \mu\text{m}$, which corresponds to > 100 times higher than that of

a blank Si-PD. Comparing the hybrid PDs with different amounts of UCNPs loading, there was a clear increase of photoresponsivity at $\lambda = 1.5 \mu\text{m}$ from UCNPs-1 to UCNPs-2 while such an increase became very small when more UCNPs were loaded (in UCNPs-3). This can be understood as the consequence of increased self absorption of the upconverted fluorescence when many layers of UCNPs were loaded on top of the Si device leading only to a mild increase of photoresponsivity from 0.008 A W^{-1} to 0.009 A W^{-1} at 1550 nm when changing the loading from UCNPs-2 to UCNPs-3. When considering the photoresponsivity in the whole spectrum window, the UCNPs-2/Si hybrid PD can offer a trade-off between the increase of photoresponsivity at around $\lambda = 1.5 \mu\text{m}$ without much sacrifice of photoresponsivity in the visible/near-IR spectrum.

Figure 4. (a) Time-dependent photocurrent (applied voltage = 0 V) of an UCNPs-2/Si-PD under the illumination of a $\lambda = 1.5 \mu\text{m}$ laser at different laser powers. (b) The responsivity/ detectivity of this UCNPs/Si-PD as a function of incident laser power. (c) Time-dependent photoresponse. (d) A zoom-in view of the time-dependent photoresponse from Figure 4c with the measured device rise/fall time (T_{rise} = rise time, and T_{fall} = fall time).

A $\lambda = 1.5 \mu\text{m}$ laser was then focused (spot diameter $\sim 1.0 \text{ mm}$) onto the surface of a UCNPs-2/Si hybrid PD to further study its time-dependent and power-dependent room-temperature photoresponse characteristics. A series of laser powers ranging from $0.05 \mu\text{W}$ to 0.2 mW were used in the experiment. A clear photoresponse in terms of the photocurrent (A) following the laser being powered on/off can be observed at different laser powers (Figure 4(a)). These data allow us to obtain the evolution of the responsivity/detectivity over different laser powers under $\lambda = 1.5 \mu\text{m}$ illumination (Figure 4(b)), which

exhibits a maximum responsivity of 11 mA W^{-1} at a laser power of $0.05 \text{ } \mu\text{W}$. Using an approximation of shot-noise limited dark currents [35] on these hybrid PDs at $\lambda = 1.5 \text{ } \mu\text{m}$, a maximum detectivity of 6.15×10^{12} Jones was obtained, representing a competitive figure-of-merit by comparison to other commercialized PDs such as InGaAs, Ge and PbS [10, 36, 37]. The same laser spot was also focused onto a blank Si-PD, a UCNPs1/Si PD and a UCNPs-3/Si PD; their photoresponse characteristics by comparison to the optimized UCNPs-2/Si PD are shown in Figure S5 of the supplementary material. Besides the responsivity and detectivity, the photoresponse time is another important parameter for evaluating these hybrid PDs. In order to investigate this aspect, the $\lambda = 1.5 \text{ } \mu\text{m}$ laser was modulated by a function generator while the photocurrent signal of the hybrid device was monitored by an oscilloscope. As both the inorganic UCNPs and Si are air-stable, stable photoresponse characteristics following the laser being powered on/off were observed in the UCNPs-2/Si hybrid PDs (Figure 4(c)). By closely examining the photoresponse characteristics of a single power on/off event, the rise and fall times of this hybrid device can be calculated, representing the time necessary for the responsivity to rise from 10% to 90% and to fall from 90% to 10%, respectively. As shown in Figure 4(d), the rise and fall times of the UCNPs-2/Si hybrid PD are $430 \text{ } \mu\text{s}$ and $650 \text{ } \mu\text{s}$, respectively. By comparison to the rise/fall time of the blank Si-PD which is $10 \text{ ns}/10 \text{ ns}$, the photoresponse time of hybrid devices is longer, which is most likely limited by the fluorescence lifetime of the applied UCNPs (see Figure S6 of the supplementary material) and the coupling between the UCNPs and the Si device underneath. Overall, with a detectivity higher than the previous works employing erbium-doped silicate nanosheet/hybrid perovskite [22] and UCNPs/conjugated polymer [28, 29] and a photoresponse time comparable to, or shorter than previous works [22], the photodetection performance of the UCNPs-Si hybrid PDs described here is highly encouraging. Here, different material systems possessing photodetection capability at $\lambda = 1.5 \text{ } \mu\text{m}$ are summarized in Table 1. Considering the photoresponse characteristics, production cost and air stability, the current UCNPs/Si system is promising for the future generation of low-cost and stable broadband photodetectors.

Table 1. Material systems and their performance for photodetection at $\lambda = 1.5 \text{ } \mu\text{m}$

Systems	Applied voltage	Responsivity	Rise time	Solution processed	Toxic heavy elements	Air Stability	Ref.
MoS ₂	10 V	33 mA/W	-	No	No	Yes	[39]
Monolayer graphene	0.1 V	0.2 A/W	50 s	No	No	Yes	[40]
Graphene-Cu _{3-x} P NC film	0 V	19.16 mA/W	0.79 s	Partly	No	No	[41]
Al ₂ O ₃ -passivated black phosphorus	0.1 V / 13.5 V	6 mA/W	0.1 ms	No	No	Yes	[16]
PbS:P3HT:PCBM	-5 V	0.5 A/W	69 μs	Yes	Pb	No	[42]
Au NRs/Pt	1 V	0.34 A/W	97 μs	Partly	No	Yes	[21]

Perovskite-erbium silicate	1 V	0.1 mA/W	0.9 ms	No	Pb	No	[22]
Erbium chloride borate - CdS nanoribbon	5 V	0.2 mA/W	44 ms	Partly	Cd	No	[34]
Erbium-doped-UCNPs:pDPPT-TT:PCBM	0 V	0.73 mA/W	80 μ s	Yes	No	No	[29]
Erbium-doped-UCNPs:Si-PD	0 V	11 mA/W	0.43 ms	Partly	No	Yes	This work

4. Conclusions

In summary, in this work we have proposed an alternative but feasible strategy for $\lambda = 1.5 \mu\text{m}$ photodetection by the formation of nanoparticle/Si hybrid photodetectors employing solution-processed colloidal UCNPs. These UCNPs/Si hybrid PDs effectively expand the spectrum response of Si up to $\lambda = 1.7 \mu\text{m}$ while maintaining the photodetection capability of Si in the visible/near-IR spectrum. At $\lambda = 1.5 \mu\text{m}$, the optimized UCNPs/Si hybrid PDs exhibited a high responsivity of 11 mA W^{-1} , a maximum room-temperature detectivity of 6.15×10^{12} Jones, and a photoresponse time of 0.4 ms. Considering the simplicity of the device's structure and the adaptability of colloidal nanoparticles to large-scale solution processes, the UCNPs/Si hybrid PDs described pave a new path to the future generation of low-cost, stable, and broadband room-temperature photodetectors sensitive to visible, near-IR and short-wave IR photons.

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References

[1] Eng P W U, Hou Q I Z, Ang Y U W, Eng G U D, An Y U F, Hen S I S, Iang Q X U, Ang Y U W, Ong H A S and Ang Y O U W 2019 Wavelength-tunable passively mode-locked all-fiber laser at $1.5 \mu\text{m}$ *Appl. Opt.* 58 5143–7

- [2] Zeng M, Artizzu F, Liu J, Singh S, Locardi F, Mara D, Hens Z and Van Deun R 2020 Boosting the Er^{3+} 1.5 μm luminescence in CsPbCl_3 perovskite nano-crystals for photonic devices operating at telecommunication wavelengths *ACS Appl. Nano Mater.* 3 4699–707
- [3] Leong D, Harry M, Reeson K J and Homewood K P 1997 A silicon/iron-disilicide light-emitting diode operating at a wavelength of 1.5 μm *Nature* 387 686–8
- [4] Ho V X, Wang Y, Ryan B, Patrick L, Jiang H X, Lin J Y and Vinh N Q 2020 Observation of optical gain in Er-Doped GaN epilayers *J. Lumin.* 221 1–5
- [5] Steinvall O 2013 Active and passive imaging NIR/SWIR performance for slant paths close to ground *Opt. InfoBase Conf. Pap.* 52 4763–78
- [6] Wartak M S 2013 Introduction Computational Photonics: *An Introduction with MATLAB* (Cambridge: Cambridge University Press) pp 1–16
- [7] Bronstein H et al 2011 Thieno[3,2-b]thiophene– diketopyrrolopyrrole-containing polymers for high-performance organic field-effect transistors and organic photovoltaic devices *J. Am. Chem. Soc.* 133 3272
- [8] Hecht J 2018 Lidar for self-driving cars *Opt. Photonics News* 29 26–33
- [9] Myers M J, Myers J D, Sarracino J T, Hardy C R, Guo B, Christian S M, Myers J A, Roth F and Myers A G 2010 LIBS system with compact fiber spectrometer, head mounted spectra display and hand held eye-safe erbium glass laser gun *Proc. SPIE* 7578 75782G
- [10] Zeller J W, Efstathiadis H, Bhowmik G, Haldar P, Dhar N K, Lewis J, Wijewarnasuriya P, Puri Y R and Sood A K 2015 Development of Ge PIN photodetectors on 300 mm Si wafers for near-infrared sensing *Int. J. Eng. Res. Technol.* 8 23-33
- [11] Xia F, Mueller T, Lin Y, Valdes-Garcia A and Avouris P 2009 Ultrafast graphene photodetector *Nat. Nanotechnol.* 4 839
- [12] Pospischil A, Humer M, Furchi M M, Bachmann D, Guider R, Fromherz T and Mueller T 2013 CMOS-compatible graphene photodetector covering all optical communication bands *Nat. Photon.* 7 892
- [13] Chen Z, Li X, Wang J, Tao L, Long M, Liang S J, Ang L K, Shu C, Tsang H K and Xu J B 2017 Synergistic effects of plasmonics and electron trapping in graphene short-wave infrared photodetectors with ultrahigh responsivity *ACS Nano* 11 430–7
- [14] Xie Y et al 2017 Ultrabroadband MoS_2 photodetector with spectral response from 445 to 2717 nm *Adv. Mater.* 29 1605972
- [15] Du H, Lin X, Xu Z and Chu D 2015 Recent developments in black phosphorus transistors *J. Mater. Chem. C* 3 8760–75

- [16] Na J, Park K, Kim J T, Choi W K and Song Y W 2017 Air-stable few-layer black phosphorus phototransistor for near-infrared detection *Nanotechnology* 28 085201
- [17] Kufer D, Nikitskiy I, Lasanta T, Navickaite G, Koppens F H L and Konstantatos G 2015 Hybrid 2D-0D MoS₂-PbS quantum dot photodetectors *Adv. Mater.* 27 176–80
- [18] Saran R and Curry R J 2016 Lead sulphide nanocrystal photodetector technologies *Nat. Photon.* 10 81
- [19] Sobhani A, Knight M W, Wang Y, Zheng B, King N S, Brown L V, Fang Z, Nordlander P and Halas N J 2013 Narrowband photodetection in the near-infrared with a plasmon-induced hot electron device *Nat. Commun.* 4 1643
- [20] Xiang H, Niu T, Schoenauer Sebag M, Hu Z, Xu X, Billot L, Aigouy L and Chen Z 2018 Short-wave infrared sensor by the photothermal effect of colloidal gold nanorods *Small* 14 1704013
- [21] Xiang H, Hu Z, Billot L, Aigouy L and Chen Z 2019 Hybrid plasmonic gold-nanorod–platinum short-wave infrared photodetectors with fast response *Nanoscale* 11 18124–31
- [22] Zhang X et al 2017 Perovskite–erbium silicate nanosheet hybrid waveguide photodetectors at the near-infrared telecommunication band *Adv. Mater.* 29 1604431
- [23] Idris N M, Jayakumar M K G, Bansal A and Zhang Y 2015 Upconversion nanoparticles as versatile light nanotransducers for photoactivation applications *Chem. Soc. Rev.* 44 1449–78
- [24] Wang F, Banerjee D, Liu Y, Chen X and Liu X 2010 Upconversion nanoparticles in biological labeling, imaging, and therapy *Analyst* 135 1839–54
- [25] Sedlmeier A and Gorris H H 2015 Surface modification and characterization of photon-upconverting nanoparticles for bioanalytical applications *Chem. Soc. Rev.* 44 1526–60
- [26] Goldschmidt J C and Fischer S 2015 Upconversion for photovoltaics – a review of materials, devices and concepts for performance enhancement *Adv. Opt. Mater.* 3 510–35
- [27] Schoenauer Sebag M, Hu Z, de Oliveira Lima K, Xiang H, Gredin P, Mortier M, Billot L, Aigouy L and Chen Z 2018 Microscopic evidence of upconversion-induced near-infrared light harvest in hybrid perovskite solar cells *ACS Appl. Energy Mater.* 1 3537–43
- [28] Zhao X, Song L, Zhao R and Tan M C 2019 High-performance and flexible shortwave infrared photodetectors using composites of rare earth-doped nanoparticles *ACS Appl. Mater. Interfaces* 11 2344–51
- [29] Xiang H, Hu Z, Billot L, Aigouy L, Zhang W, McCulloch I and Chen Z 2019 Heavy-metal-free flexible hybrid polymer-nanocrystal photodetectors sensitive to 1.5 μm wavelength *ACS Appl. Mater. Interfaces* 11 42571–9

- [30] Zhao J, Sun Y, Kong X, Tian L, Wang Y, Tu L, Zhao J and Zhang H 2008 Controlled synthesis, formation mechanism, and great enhancement of red upconversion luminescence of NaYF₄: Yb³⁺, Er³⁺ nanocrystals/submicroplates at low doping level *J. Phys. Chem. B* 112 15666–72
- [31] Liu D, Jing Y, Wang K, Wang Y and Luo G 2019 Reaction study of α -phase NaYF₄:Yb,Er generation via a tubular microreactor: discovery of an efficient synthesis strategy *Nanoscale* 11 8363–71
- [32] Zhang Y, Li S, Qin F, Zhang Z and Dai Z 2015 Ultraviolet and visible upconversion luminescence in Y₂O₃:Er³⁺, Gd³⁺ microcrystals by 155 μ m excitation *J. Opt. Soc. Am. B* 32 1856
- [33] Fu Y, Qi Z, Xu X, Li L, Wang X, Zhu X, Zhuang X and Pan A 2019 Near-infrared photodetection based on erbium chloride borate nanobelts *Appl. Phys. Express* 12 035001
- [34] Faulkner D O, McDowell J J, Price A J, Perovic D D, Kherani N P and Ozin G A 2012 Measurement of absolute photoluminescence quantum yields using integrating spheres - Which way to go? *Laser Photonics Rev.* 6 802–6
- [35] Dou L, Yang Y M, You J, Hong Z, Chang W H, Li G and Yang Y 2014 Solution-processed hybrid perovskite photodetectors with high detectivity *Nat. Commun.* 5 1–6
- [36] Rogalski A 2012 Progress in focal plane array technologies *Prog. Quantum Electron.* 36 342–473
- [37] Conley B R et al 2014 Si based GeSn photoconductors with a 1.63 A W⁻¹ peak responsivity and a 2.4 μ m long-wavelength cutoff *Appl. Phys. Lett.* 105 221117
- [38] Zhang B Y, Liu T, Meng B, Li X, Liang G, Hu X and Wang Q J 2013 Broadband high photoresponse from pure monolayer graphene photodetector *Nat. Commun.* 4 1811
- [39] Sun T et al 2017 Flexible broadband graphene photodetectors enhanced by plasmonic Cu_{3-x}P colloidal nanocrystals *Small* 13 1–9
- [40] Rauch T, Böberl M, Tedde S F, Fürst J, Kovalenko M V, Hesser G, Lemmer U, Heiss W and Hayden O 2009 Near-infrared imaging with quantum-dot-sensitized organic photodiodes *Nat. Photon.* 3 332–6