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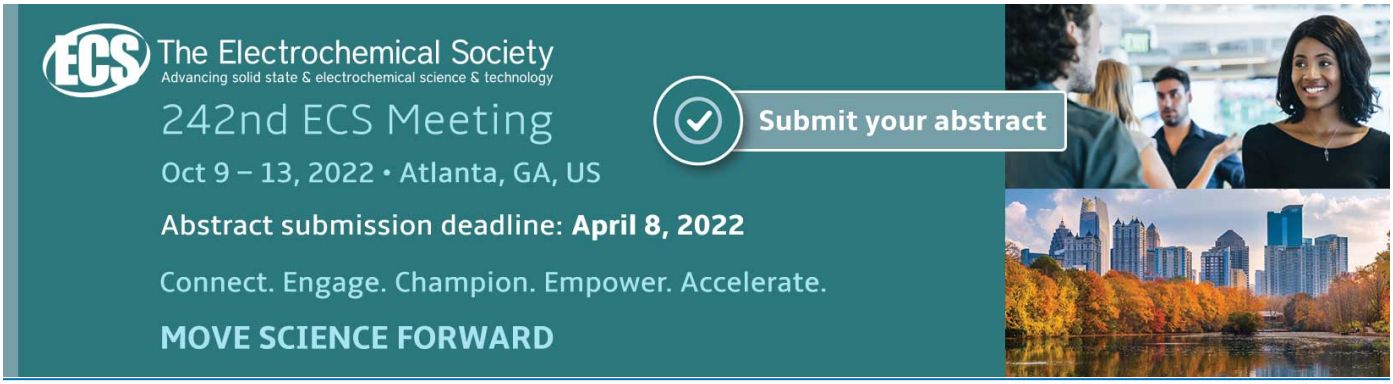

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Quantum dots/graphene nanohybrids photodetectors: progress and perspective

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Abstract

Semiconductor quantum dots/graphene heterostructure nanohybrids combine the advantages of the enhanced light–matter interaction and spectral tunability of quantum dots (QDs) and high charge mobility in graphene as a charge transport pathway, providing a unique platform for exploration of photodetectors with high performance. In particular, the QDs/graphene nanohybrids allow resolution to the critical issue of charge transport in QDs-only photodetectors stemming from the low charge mobility associated with both QD surface defect states and inter-QD junctions. Furthermore, the achieved capability in industrial-scale fabrication of graphene and colloidal QDs has motivated efforts in research of QDs/graphene nanohybrids focal plane arrays that are expected to be not only high performance and low cost, but also light-weight, flexible and wearable. This paper aims to highlight recent progress made in the research and development of QDs/graphene nanohybrid photodetectors and discuss the challenges remained towards their commercial applications.

1. Introduction

Graphene regards to a monolayer of carbon atoms arranged in a two-dimensional honeycomb lattice [1, 2] Its discovery in 2004 has not only led the 2010 Nobel Prize in Physics to Geim and Novoselov, but also an intensive interest in research and development for a large spectrum applications taking advantage of graphene's unique physical properties of high charge carrier mobility predicted to be up to 200,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at room temperature, broadband optical transparency of 97.7% from near ultraviolet to mid-infrared, high mechanical strength, flexibility and chemical stability [1–4]. Graphene can be viewed as an atomically thin (thickness ~0.34 nm) film and can be grown using chemical vapor deposition in large area [5, 6] with compatibility to the established microfabrication processes[7] for graphene-based devices and circuits for applications in electronic, photonic, optoelectronic, sensors, etc [8–16].

Graphene-based photodetectors [1, 17–19] present a particular interesting topic considering the broadband absorption of ~2.3% per graphene sheet. However, graphene is a semimetal with a zero bandgap *Eg* [4], which has limited its use in a similar way to conventional semiconductors of well-defined *Eg*. This has motivated a recent exploration of quantum dots (QDs) on graphene heterostructure nanohybrids (QDs/graphene, which is a specific form of more general graphene/semiconductor nanohybrids) for photodetection with a high photoconductive gain and hence high responsivity [20–35]. These QDs/graphene nanohybrids build on the exciting progress made recently in colloidal QDs of a larger number semiconductors [36–52] and graphene [1–4, 53–56]. The QDs/graphene nanohybrids take advantage of the strong quantum confinement of QDs with enhanced light–matter interaction, spectral tunability by controlling their composition, shape, dimension, functionality, and carrier doping [57, 58], and of the extraordinary charge mobility of graphene at room temperature [1, 3, 53, 56]. In these devices, there are two main steps to realize the optical-to-electrical signal conversion. First, the QDs play the role of photosensitizers and absorb the incident photons. The produced excitons (or electron-hole pairs) can then be dissociated at the QDs/graphene interface by the built-in electric

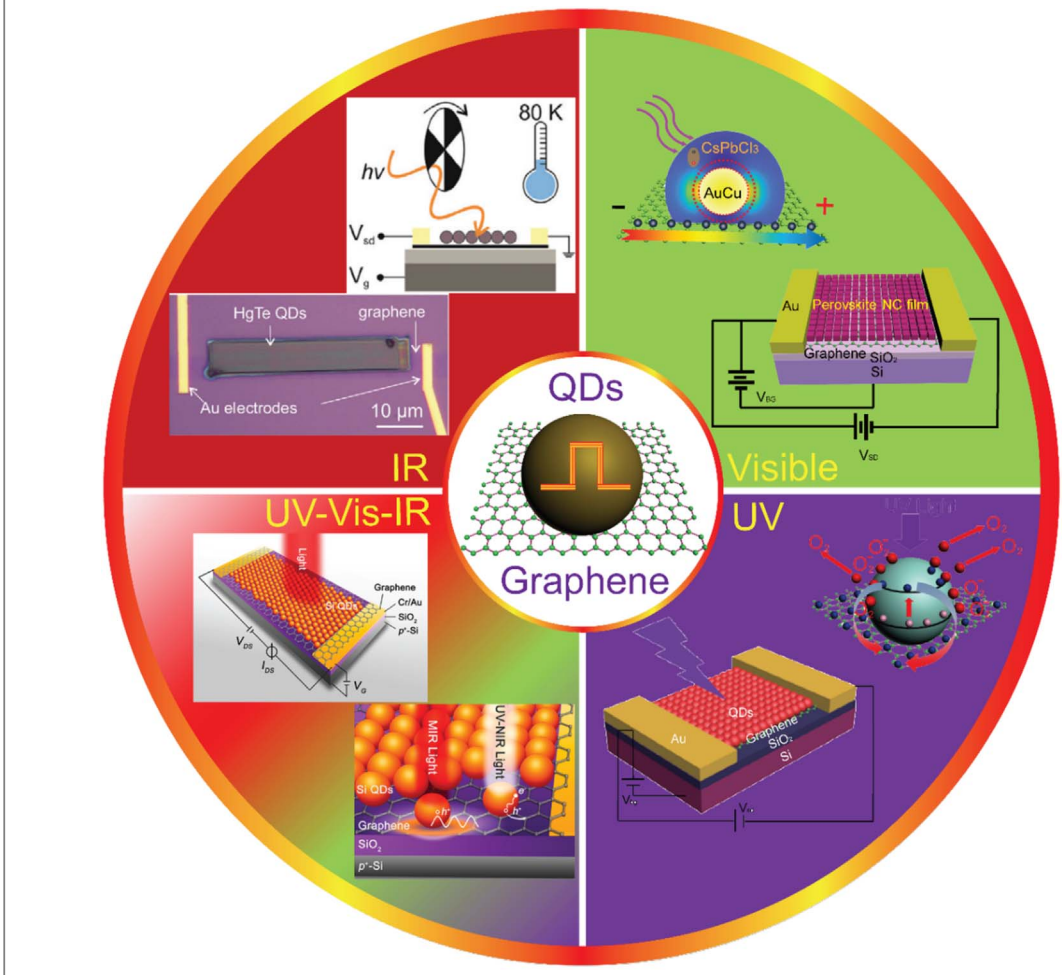

Figure 1. A few examples of the QDs/graphene nanohybrid photodetectors for UV, Visible, IR and UV-Vis-IR broadband detection. Reproduced with permission. [23] Copyright 2017, American Chemical Society. Reproduced with permission. [25] Copyright 2019, American Chemical Society. Reproduced with permission. [67] Copyright 2020, John Wiley and Sons. Reproduced with permission. [76] Copyright 2021, John Wiley and Sons. Reproduced with permission. [75] Copyright 2017, American Chemical Society.

field associated to the QD/graphene band-edge alignment. Secondly, the free charge carriers are transferred from QDs to graphene channel under the same built-in field and collected by the source and drain electrodes on the channel. The high mobility in exceeding 1.0×10^4 $cm^2 \cdot V^{-1} \cdot s^{-1}$ experimentally achieved in graphene at room temperature [18, 59], which could be further enhanced through sample optimization, can lead to high photoconductive gain (G) $> 10^{10}$ in various QDs/graphene nanohybrids photodetectors [23, 25, 27, 60–67] and hence high photoresponsivity (R) and figure-of-merit specific detectivity (D^*) [24, 26, 27].

After the first report of Pubs QDs/graphene photodetectors by Konstantinos *et al* in 2012 [27], many QDs/graphene nanohybrid photodetectors have been explored in ultraviolet (UV), visible (vis), and infrared (IR) spectra [23, 26, 27, 68–72]. High D^* values in the range of $10^{11}-10^{16}$ Jones have been reported in a broad spectrum ranging from IR ($0.8-3$ μm) [27], visible (400 nm − 700 nm)[73] to UV detections (300 nm − 400 nm) [25–27, 73], figure 1 illustrates several examples of the QDs/graphene nanohybrid photodetectors [23, 25, 66, 74, 75]. On an all-printable ZnO QDs/graphene UV photodetector, the presence of an atomically thin insulating surface layer on ZnO QDs was found to block the charge transfer from QD to graphene, and removing such a layer has demonstrated critical to the achievement of high $G \sim 3.6 \times 10^9$, $R \sim 9.9 \times 10^8$ A W^{-1}, and D^* of 1×10^{14} Jones in this device [23]. Gong *et al* reported a broadband photosensitizer based on FeS_2 nanocubes (NCs) that exhibits a strong localized surface plasmonic resonance (LSPR) effect with enhanced light absorption and expanded spectral range beyond the cutoff of FeS_2 covering the UV–visible-SWIR (SWIR regards to short-wave IR) broadband with responsivities reaching 1.08×10^6 A W^{-1} [26]. Ni *et al* reported broadband UV to mid-infrared (MIR) photodetection using plasmonic Si QDs doped with boron (B) for LSPR enhancement. These B-doped Si QDs/graphene photodetectors exhibited high $G \sim 10^{12}$, $R \sim 10^9$ A W^{-1}, and $D^* \sim 10^{13}$ Jones [74]. Besides doping semiconductor QDs to produce LSPR for broadband and enhanced absorption, metal/semiconductor core/shell QDs use plasmonic metal cores for light trapping, which can lead to improved light absorption on semiconductor shell. Using a template modulated colloidal approach for

synthesizing AuCu core (~7.1 nm in diameter) [76–78], followed with growth of metal-halide perovskite shell ($CsPbCl_3$) shell [66], enhanced light absorption was observed in the AuCu/$CsPbCl_3$ core/shell QDs as compared to $CsPbCl_3$ QDs of comparable total diameter~10 nm. A remarkable 30 times-enhanced photoresponse in AuCu/$CsPbCl_3$ core/shell QDs/graphene nanohybrid photodetectors, as compared to the counterparts of $CsPbCl_3$ QD/graphene, was observed and attributed to the light trapping by AuCu core and enhanced light absorption in $CsPbCl_3$ shell, as confirmed in a Finite-Difference Time-Domain (FDTD) simulation [79]. A recent work by Alamri *et al*[80] combined the plasmonic effects from WS_2 nanodiscs grown on graphene and from Ag nanoparticles (AgNPs), leading to a seven-fold enhancement in photoresponse. Recently, Grotevent *et al* employed the HgTe QDs combined with graphene forming HgTe QDs/graphene nanohybrids photodetectors. The spectral sensitivity of this device has been extended to MIR range up to 3 μm. At 80 K, the D^*~6×10^8 Jones at a wavelength of 2.5 μm and a frequency of 67 Hz was obtained [75].

QDs/graphene nanohybrids can be fabricated by depositing QDs on graphene using various low-cost, scalable methods including spin-coating [52, 74, 81–84], inkjet printing [16, 23, 85–89] and direct growth [80, 90–92], which illustrates additional advantages of QD/graphene nanohybrids including low cost, monolithic, flexible, wearable, etc In addition, different QDs targeting at different spectral ranges may be mixed or pixelated for multi-color, broadband photodetection [24, 85]. Moreover, a 288 $\times$ 388 channel focal plane array of PbS QDs/graphene nanohybrid photodetectors have been integrated with Si-based readout circuit, illustrating the potential of QD/graphene nanohybrid photodetectors for practical applications [21].

Despite progress made in research and development of QDs/graphene nanohybrid photodetectors, challenges remain and must be addressed before commercial applications of these photodetectors can be realized. A major challenge is in atomic-scale control of the QDs/graphene heterojunction interface that directly affects the exciton dissociation and charge transfer, which in turn impact the device performance including both photoresponse and response speed. For example, an atomically thin Zn acetate or Zn(Ac) layer on the ZnO QDs can completely block the charge transfer from ZnO QDs to graphene and lead to negligible photoresponse to UV light. When this surface layer is removed, improved photoresponse by orders of magnitude can be obtained [23]. On the other hand, many QDs such as PbS and $CsPbX_3$ (X = Cl, Br, I), have surface states due to the presence of defects and dangling bonds on the QDs surface, which not only lead to QDs decomposition in ambient but also behave as charge traps at the QDs/graphene interface that degrade both photoresponse and response speed by orders of magnitude [67, 93]. Ligand-exchange has been adopted for passivation of such surface states and hence improvement of photodetector performance [23, 24, 27, 94, 95]. Vafaie *et al* developed an efficient ligand-exchange route that tailors the halide passivants and removes unwanted organic species, and improves charge transport. In PbS QDs based photodetectors, this ligand-exchange protocol gave rise to a high external quantum efficiency of 80% at 1550 nm, D^*~8×10^{11} Jones, and a 10 ns response time [96]. Gong *et al* replaced insulating oleic acid and oleylamine with conducting 3-mercaptopropionic acid ligands in the $CsPbCl_3$ QDs/graphene photodetectors with significantly improved device stability and performance [25]. It should be noted that the approaches developed for such interface engineering are QDs specific and hence cannot be applied universally. This means a continuous effort in research and development of various new interface engineering approaches for high-efficiency charge transfer across the QDs/graphene interface and for longevity of the QD/graphene nanohybrids devices will be a focus of future research with discovery of new functional QDs. Another major challenge is the limited light absorption in QDs/graphene nanohybrids that have a thin layer of QDs. It should be realized that multilayer QDs may have enhanced light absorption while the benefit can be significantly reduced by the inter-QD junctions that are hurdles to charge transport [24, 29, 97]. Development of schemes for light management will be important in future research to enhance light absorption of the very thin QD layer. Finally, an additional challenge is associated with device nonuniformity due to lack of a precise control in QDs (dimension, surface states, distribution on graphene, stacking in multilayer cases, etc) and QDs/graphene interface. All of the above present a series of roadblocks that must be removed to achieve high performance, uniformity and yield in commercial application of QDs/graphene based focal plane arrays.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Geim A K and Novoselov K S 2007 The rise of graphene *Nat. Mater.* **6** 183–91
[2] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 Electric field effect in atomically thin carbon films *Science* **306** 666–9
[3] Chen J H, Jang C, Xiao S D, Ishigami M and Fuhrer M S 2008 Intrinsic and extrinsic performance limits of graphene devices on SiO_2 *Nat. Nanotechnol.* **3** 206–9
[4] Novoselov K S, Geim A K, Morozov S V, Jiang D, Katsnelson M I, Grigorieva I V, Dubonos S V and Firsov A A 2005 Two-dimensional gas of massless dirac fermions in graphene *Nature* **438** 197–200
[5] Li X S *et al* 2009 Large-area synthesis of high-quality and uniform graphene films on copper foils *Science* **324** 1312–4
[6] Sun B J *et al* 2021 Synthesis of wafer-scale graphene with chemical vapor deposition for electronic device applications *Adv. Mater. Technol.* **79** 2000744
[7] Wei T, Bao L P, Hauke F and Hirsch A 2020 Recent advances in graphene patterning *ChemPlusChem* **85** 1655–68
[8] Mandal P, Debbarma J and Saha M 2021 A review on the emergence of graphene in photovoltaics industry *Biointerface Res. Appl. Chem.* **11** 15009–36
[9] Wang C Y, Wang Y Y, Yang Z and Hu N T 2021 Review of recent progress on graphene-based composite gas sensors *Ceram. Int.* **47** 18
[10] Chung S, Revia R A and Zhang M Q 2021 Graphene quantum dots and their applications in bioimaging, biosensing, and therapy *Adv. Mater.* **33** 26
[11] Li Z L, Chen Y P, Ma T Y, Jiang Y Z, Chen J, Pan H G and Sun W P 2021 2D metal-free nanomaterials beyond graphene and its analogues toward electrocatalysis applications *Adv. Energy Mater.* **13** 2101202
[12] Li X M and Chai Y 2021 Design and applications of graphene-based flexible and wearable physical sensing devices *2D Mater.* **8** 14
[13] Doscher H and Reiss T 2021 Graphene roadmap briefs (no. 1): innovation interfaces of the graphene flagship *2D Mater.* **8** 022004
[14] Doscher H, Schmaltz T, Neef C, Thielmann A and Reiss T 2021 Graphene roadmap briefs (no. 2): industrialization status and prospects 2020 *2D Mater.* **8** 022005
[15] Junaid M, Khir M H M, Witjaksono G, Ullah Z, Tansu N, Saheed M S M, Kumar P, Wah L H, Magsi S A and Siddiqui M A 2020 A review on graphene-based light emitting functional devices *Molecules* **25** 32
[16] Wu J Z 2018 Graphene. *Transparent Conductive Materials: Materials, Synthesis,Characterization, Applications* ed D Levy and E Castellón 1/2 (Weinheim: Wiley)
[17] Mueller T, Xia F N A and Avouris P 2010 Graphene photodetectors for high-speed optical communications *Nat. Photonics* **4** 297–301
[18] Bonaccorso F, Sun Z, Hasan T and Ferrari A C 2010 Graphene photonics and optoelectronics *Nat. Photonics* **4** 611–22
[19] Xia F N, Mueller T, Lin Y M, Valdes-Garcia A and Avouris P 2009 Ultrafast graphene photodetector *Nat. Nanotechnol.* **4** 839–43
[20] Koppens F H L, Mueller T, Avouris P, Ferrari A C, Vitiello M S and Polini M 2014 Photodetectors based on graphene, other two-dimensional materials and hybrid systems *Nat. Nanotechnol.* **9** 780–93
[21] Goossens S *et al* Broadband image sensor array based on graphene–CMOS integration *Nat. Photonics* 2017 **11** 366–71
[22] Gong M, Ewing D, Casper M, Stramel A, Elliot A and Wu J Z 2019 Controllable synthesis of monodispersed $Fe_{1-x}S_2$ nanocrystals for high-performance optoelectronic devices *ACS Appl. Mater. Interfaces* **11** 19286–93
[23] Gong M, Liu Q, Cook B, Kattel B, Wang T, Chan W L, Ewing D, Casper M, Stramel A and Wu J Z 2017 All-printable ZnO quantum dots/graphene van der waals heterostructures for ultrasensitive detection of ultraviolet light *ACS Nano* **11** 4114–23
[24] Gong M, Liu Q, Goul R, Ewing D, Casper M, Stramel A, Elliot A and Wu J Z 2017 Printable nanocomposite FeS_2-PbS nanocrystals/graphene heterojunction photodetectors for broadband photodetection *ACS Appl. Mater. Interfaces* **9** 27801–8
[25] Gong M, Sakidja R, Goul R, Ewing D, Casper M, Stramel A, Elliot A and Wu J Z 2019 High-performance all-inorganic $CsPbCl_3$ perovskite nanocrystal photodetectors with superior stability *ACS Nano* **13** 1772–83
[26] Gong M, Sakidja R, Liu Q, Goul R, Ewing D, Casper M, Stramel A, Elliot A and Wu J Z 2018 Broadband photodetectors enabled by localized surface plasmonic resonance in doped iron pyrite nanocrystals *Adv. Opt. Mater.* **6** 1701241
[27] Konstantatos G, Badioli M, Gaudreau L, Osmond J, Bernechea M, de Arquer F P G, Gatti F and Koppens F H L 2012 Hybrid graphene-quantum dot phototransistors with ultrahigh gain *Nat. Nanotechnol.* **7** 363–8
[28] Di Bartolomeo A, Luongo G, Iemmo L, Urban F and Giubileo F 2018 Graphene–silicon schottky diodes for photodetection *IEEE Trans. Nanotechnol.* **17** 1133–7
[29] Wu J Z and Gong M 2021 Nanohybrid photodetectors *Adv. Photonics Res.* **2** 2100015
[30] De Fazio D *et al* Graphene-quantum dot hybrid photodetectors with low dark-current readout *ACS Nano* 2020 **14** 11897–905
[31] Liu Q, Tian H, Li J, Hu A, He X, Sui M and Guo X 2019 Hybrid graphene/Cu_2O quantum dot photodetectors with ultrahigh responsivity *Adv. Opt.l Mater.* **7** 1900455
[32] Zhao Y, Feng X, Zhao M, Zheng X, Liu Z, Yang S, Tang S, Chen D, Wang G and Ding G 2021 High-performance near-infrared photodetectors based on C_3N quantum dots integrated with single-crystal graphene *J. Mater. Chem. C* **9** 1333–8
[33] Chen K, Zhang C, Zang X, Ma F, Chen Y and Dan Y 2021 Explicit gain equations for hybrid graphene-quantum-dot photodetectors *Small* **17** e2006307
[34] Nian Q, Gao L, Hu Y, Deng B, Tang J and Cheng G J 2017 Graphene/PbS-quantum dots/graphene sandwich structures enabled by laser shock imprinting for high performance photodetectors *ACS Appl. Mater. Interfaces* **9** 44715–23
[35] Tong L, Qiu F, Zeng T, Long J, Yang J, Wang R, Zhang J, Wang C, Sun T and Yang Y 2017 Recent progress in the preparation and application of quantum dots/graphene composite materials *RSC Adv.* **7** 47999–8018
[36] Kovalenko M V *et al* Prospects of nanoscience with nanocrystals *ACS Nano* 2015 **9** 1012–57
[37] Murray C B, Sun S, Gaschler W, Doyle H, Betley T A and Kagan C R 2001 Colloidal synthesis of nanocrystals and nanocrystal superlattices *IBM J. Res. Dev.* **45** 47–56
[38] Sablon K A, Sergeev A, Najmaei S and Dubey M 2017 High-response hybrid quantum dots- 2D conductor phototransistors: recent progress and perspectives *Nanophotonics* **6** 1263–80

[39] Talapin D V, Lee J S, Kovalenko M V and Shevchenko E V 2010 Prospects of colloidal nanocrystals for electronic and optoelectronic applications *Chem. Rev.* **110** 389–458
[40] Chen K, Wang C, Peng Z, Qi K, Guo Z, Zhang Y and Zhang H 2020 The chemistry of colloidal semiconductor nanocrystals: from metal-chalcogenides to emerging perovskite *Coord. Chem. Rev.* **418** 213333
[41] Owen J and Brus L 2017 Chemical synthesis and luminescence applications of colloidal semiconductor quantum dots *J. Am. Chem. Soc.* **139** 10939–43
[42] Ma Y, Zhang Y and Yu W W 2019 Near infrared emitting quantum dots: synthesis, luminescence properties and applications *J. Mater. Chem. C* **7** 13662–79
[43] Lu H, Carroll G M, Neale N R and Beard M C 2019 Infrared quantum dots: progress, challenges, and opportunities *ACS Nano* **13** 939–53
[44] Evans C M, Cass L C, Knowles K E, Tice D B, Chang R P H and Weiss E A 2012 Review of the synthesis and properties of colloidal quantum dots: the evolving role of coordinating surface ligands *J. Coord. Chem.* **65** 2391–414
[45] Green M and Mirzai H 2018 Synthetic routes to mercury chalcogenide quantum dots *J. Mater. Chem. C* **6** 5097–112
[46] Jing L, Kershaw S V, Li Y, Huang X, Li Y, Rogach A L and Gao M 2016 Aqueous based semiconductor nanocrystals *Chem. Rev.* **116** 10623–730
[47] Akkerman Q A, Raino G, Kovalenko M V and Manna L 2018 Genesis, challenges and opportunities for colloidal lead halide perovskite nanocrystals *Nat. Mater.* **17** 394–405
[48] Shamsi J, Urban A S, Imran M, De Trizio L and Manna L 2019 Metal halide perovskite nanocrystals: synthesis, post-synthesis modifications, and their optical properties *Chem. Rev.* **119** 3296–348
[49] Pu Y, Cai F, Wang D, Wang J-X and Chen J-F 2018 Colloidal synthesis of semiconductor quantum dots toward large-scale production: a review *Ind. Eng. Chem. Res.* **57** 1790–802
[50] Murray C B, Kagan C R and Bawendi M G 2000 Synthesis and characterization of monodisperse nanocrystals and close-packed nanocrystal assemblies *Annu. Rev. Mater. Sci.* **30** 545–610
[51] Shu Y, Lin X, Qin H, Hu Z, Jin Y and Peng X 2020 Quantum dots for display applications *Angew. Chem. Int. Ed.* **59** 22312–23
[52] García de Arquer F P, Armin A, Meredith P and Sargent E H 2017 Solution-processed semiconductors for next-generation photodetectors *Nat. Rev. Mater.* **2** 16100
[53] Geim A K G 2009 Status and prospects *Science* **324** 1530–4
[54] Zhang Y B, Tan Y W, Stormer H L and Kim P 2005 Experimental observation of the quantum hall effect and berry's phase in graphene *Nature* **438** 201–4
[55] Avouris P, Chen Z H and Perebeinos V 2007 Carbon-based electronics *Nat. Nanotechnol.* **2** 605–15
[56] Dean C R *et al* Boron nitride substrates for high-quality graphene electronics *Nat. Nanotechnol.* 2010 **5** 722–6
[57] Luther J M, Jain P K, Ewers T and Alivisatos A P 2011 Localized surface plasmon resonances arising from free carriers in doped quantum dots *Nat. Mater.* **10** 361–6
[58] Wu J, Lu Y, Feng S, Wu Z, Lin S, Hao Z, Yao T, Li X, Zhu H and Lin S 2018 The interaction between quantum dots and graphene: the applications in graphene-based solar cells and photodetectors *Adv. Funct. Mater.* **28** 1804712
[59] Bae S *et al* Roll-to-roll production of 30-inch graphene films for transparent electrodes *Nat. Nanotechnol.* 2010 **5** 574–8
[60] Xia F, Wang H, Xiao D, Dubey M and Ramasubramaniam A 2014 Two-dimensional material nanophotonics *Nat. Photonics* **8** 899–907
[61] Geim A K and Grigorieva I V 2013 Van der waals heterostructures *Nature* **499** 419–25
[62] Roy S, Aguirre A, Higgins D A and Chikan V 2012 Investigation of charge transfer interactions in CdSe nanorod P3HT/PMMA blends by optical microscopy *J. Phys. Chem. C* **116** 3153–60
[63] Zhang W J *et al* Ultrahigh-gain photodetectors based on atomically thin graphene-MoS_2 heterostructures *Sci. Rep.* 2014 **4** 3826
[64] Zhang W J, Huang J K, Chen C H, Chang Y H, Cheng Y J and Li L J 2013 High-gain phototransistors based on a CVD MoS_2 monolayer *Adv. Mater.* **25** 3456–61
[65] Roy K, Padmanabhan M, Goswami S, Sai T P, Ramalingam G, Raghavan S and Ghosh A 2013 Graphene–MoS_2 hybrid structures for multifunctional photoresponsive memory devices *Nat. Nanotechnol.* **8** 826–30
[66] Gong M, Alamri M, Ewing D, Sadeghi S M and Wu J Z 2020 Localized surface plasmon resonance enhanced light absorption in AuCu/$CsPbCl_3$ core/shell nanocrystals *Adv. Mater.* **32** 2002163
[67] Lu R T, Liu J W, Luo H F, Chikan V and Wu J Z 2016 Graphene/GaSe-nanosheet hybrid: towards high gain and fast photoresponse *Sci. Rep.* **6** 19161
[68] Sun Z H, Liu Z K, Li J H, Tai G A, Lau S P and Yan F 2012 Infrared photodetectors based on CVD-grown graphene and PbS quantum dots with ultrahigh responsivity *Adv. Mater.* **24** 5878–83
[69] Zhang D Y, Gan L, Cao Y, Wang Q, Qi L M and Guo X F 2012 Understanding charge transfer at PbS-decorated graphene surfaces toward a tunable photosensor *Adv. Mater.* **24** 2715–20
[70] Gong M, Kirkeminde A, Xie Y, Lu R, Liu J, Wu J Z and Ren S 2013 Iron pyrite (FeS_2) broad spectral and magnetically responsive photodetectors *Adv. Opt. Mater.* **1** 78–83
[71] Gong M G, Adhikaru P, Gong Y P, Wang, Liu Q F, Kafle B, Ching W Y, Chan W L and Wu J Z 2018 Polarity-controlled attachment of cytochrome c for high-performance cytochrome c/graphene van der waals heterojunction photodetectors *Adv. Funct. Mater.* **28** 1704797
[72] Liu B, López-González L E, Alamri M, Velázquez-Contrera E F, Santacruz-Ortega H and Wu J Z 2020 Cation–π interaction assisted molecule attachment and photocarrier transfer in rhodamine/graphene heterostructures *Adv. Mater. Interfaces* **7** 2000796
[73] Kwak D-H, Lim D-H, Ra H-S, Ramasamy P and Lee J-S 2016 High performance hybrid graphene–$CsPbBr_3$−XIX perovskite nanocrystal photodetector *RSC Adv.* **6** 65252–6
[74] Ni Z *et al* Plasmonic silicon quantum dots enabled high-sensitivity ultrabroadband photodetection of graphene-based hybrid phototransistors *ACS Nano* 2017 **11** 9854–62
[75] Grotevent M J, Hail C U, Yakunin S, Bachmann D, Calame M, Poulikakos D, Kovalenko M V and Shorubalko I 2021 Colloidal HgTe quantum dot/graphene phototransistor with a spectral sensitivity beyond 3 μm *Adv. Sci.* **8** 2003360
[76] Gong M, Kirkeminde A, Wuttig M and Ren S 2014 Phase transformation-induced tetragonal FeCo nanostructures *Nano Lett.* **14** 6493–8
[77] Gong M, Jin X, Sakidja R and Ren S 2015 Synergistic strain engineering effect of hybrid plasmonic, catalytic, and magnetic core–shell nanocrystals *Nano Lett.* **15** 8347–53
[78] Gong M, Kirkeminde A, Skomski R, Cui J and Ren S 2014 Template-directed FeCo nanoshells on AuCu *Small* **10** 4118–22
[79] Liu B, Gutha R R, Kattel B, Alamri M, Gong M, Sadeghi S M, Chan W-L and Wu J Z 2019 Using silver nanoparticles-embedded silica metafilms as substrates to enhance the performance of perovskite photodetectors *ACS Appl. Mater. Interfaces* **11** 32301–9

[80] Alamri M, Liu B, Sadeghi S M, Ewing D, Wilson A, Doolin J L, Berrie C L and Wu J 2020 Graphene/WS_2 nanodisk van der waals heterostructures on plasmonic Ag nanoparticle-embedded silica metafilms for high-performance photodetectors *ACS Appl. Nano Mater.* **3** 7858–68
[81] Liang Z, Zhang Q, Wiranwetchayan O, Xi J, Yang Z, Park K, Li C and Cao G 2012 Effects of the morphology of a ZnO buffer layer on the photovoltaic performance of inverted polymer solar cells *Adv. Funct. Mater.* **22** 2194–201
[82] Li C, Huang W, Gao L, Wang H, Hu L, Chen T and Zhang H 2020 Recent advances in solution-processed photodetectors based on inorganic and hybrid photo-active materials *Nanoscale* **12** 2201–27
[83] Shin D H and Choi S H 2018 Graphene-based semiconductor heterostructures for photodetectors *Micromachines* **9** 350
[84] Yu T, Wang F, Xu Y, Ma L, Pi X and Yang D 2016 Graphene coupled with silicon quantum dots for high-performance bulk-silicon-based schottky-junction photodetectors *Adv. Mater.* **28** 4912–9
[85] Cook B, Gong M, Ewing D, Casper M, Stramel A, Elliot A and Wu J 2019 Inkjet printing multicolor pixelated quantum dots on graphene for broadband photodetection *ACS Appl. Nano Mater.* **2** 3246–52
[86] Calvert P 2001 Inkjet printing for materials and devices *Chem. Mater.* **13** 3299–305
[87] Hossain R F, Deaguero I G, Boland T and Kaul A B 2017 Biocompatible, large-format, inkjet printed heterostructure MoS_2-graphene photodetectors on conformable substrates *Npj 2D Mater. Appl.* **1** 28
[88] Cook B, Liu Q F, Gong M G, Ewing D, Casper M, Stramel A and Wu J 2017 Quantum dots-facilitated printing of ZnO nanostructure photodetectors with improved performance *ACS Appl. Mater. Interfaces* **9** 23189–94
[89] Cook B, Liu Q F, Liu J W, Gong M G, Ewing D, Casper M, Stramel A and Wu J D 2017 Facile zinc oxide nanowire growth on graphene via a hydrothermal floating method: towards debye length radius nanowires for ultraviolet photodetection *J. Mater. Chem. C* **5** 10087–93
[90] Kim Y T, Shin H W, Ko Y S, Ahn T K and Kwon Y U 2013 Synthesis of a CdSe-graphene hybrid composed of CdSe quantum dot arrays directly grown on CVD-graphene and its ultrafast carrier dynamics *Nanoscale* **5** 1483–8
[91] Pradhan B *et al* Ultrasensitive and ultrathin phototransistors and photonic synapses using perovskite quantum dots grown from graphene lattice *Sci. Adv.* 2020 **6** eaay5225
[92] Alamri M, Gong M, Cook B, Goul R and Wu J Z 2019 Plasmonic WS_2 nanodiscs/graphene van der waals heterostructure photodetectors *ACS Appl. Mater. Interfaces* **11** 33390–8
[93] Wu J, Gong M G, Schmitz R and Liu C 2021 B. Development of high-speed quantum dots/graphene infrared detectors for uncooled infrared imaging *Proc. SPIE* **11741** 117410F
[94] Turyanska L *et al* Ligand-induced control of photoconductive gain and doping in a hybrid graphene–quantum dot transistor *Adv. Electron. Mater.* 2015 **1** 1500062
[95] Gong M G, Timalsina B, Sakidja R, Douglas J T and Wu J Z 2021 Ligands anchoring stabilizes metal halide perovskite nanocrystals *Adv. Opt. Mater.* (https://doi.org/10.1002/adom.202101012)
[96] Vafaie M, Fan J Z, Morteza Najarian A, Ouellette O, Sagar L K, Bertens K, Sun B, García de Arquer F P and Sargent E H 2021 Colloidal quantum dot photodetectors with 10-ns response time and 80% quantum efficiency at 1,550 nm *Matter* **4** 1042–53
[97] Wu J Z, Gong M G, Schmitz R C and Li B 2021 Quantum dot/graphene heterostructure nanohybrid photodetectors *Quantum Dot/Graphene Heterostructure Nanohybrid Photodetectors* ed Y M You (New York, NY: Springer)