MAPbBr$_3$ single crystal based metal-semiconductor-metal photodetector enhanced by localized surface plasmon

Ziqi Zhang$^{1,2}$, Kang Chen$^1$, Wei Xia$^{1,4}$ and Zhiyuan Zuo$^{1,2}$

$^1$ Center for Optics Research and Engineering, Shandong University, Qingdao 266237, People’s Republic of China
$^2$ Key Laboratory of Laser and Infrared System, Shandong University, Ministry of Education, Shandong University, Qingdao 266237, People’s Republic of China
$^3$ Shandong Huaguang Optoelectronics Co., Ltd., Jinan 250000, People’s Republic of China
$^4$ School of Physics and Technology, University of Jinan, Jinan 250022, People’s Republic of China

E-mail: zuozhiyuan@sdu.edu.cn

Keywords: MAPbBr$_3$, single crystal, MSM photodetector, surface plasmon, performances enhancement, ion migration

Abstract

Hybrid organic-inorganic lead halide perovskites (HOIPs) have appealed to researchers on account of excellent optoelectronic properties. Compared with films which possess grain boundaries, HOIPs single crystals with fewer defects behave excellent transport and recombination performances. In the family of HOIPs, single crystals of MAPbX$_3$ (MA = CH$_3$NH$_3^+$, X = Cl, Br or I) are recognized as the most competitive candidates for optoelectronic applications. However, the photodetectors based on MAPbX$_3$ have difficulties in detecting weak signals for lacking of gains without structure optimizations and extra energy transfer channels. In this study, taking advantage of MAPbBr$_3$ single crystal (100) facets, planar metal-semiconductor-metal (MSM) photodetectors were fabricated with Au zigzag electrodes and modified Au nanoparticles (NPs) to realize localized Au surface plasmons (SPs). Compared to device without Au NPs, 2 times enhancement of photocurrent and responsivity have been achieved under 630 nm photon irradiation and 5 V bias. Furthermore, the surface metal structures can inhibit ionic migration to a certain extent. Potential mechanisms of the enhancements and suppressions are discussed in details to reveal the applications of this technique.

1. Introduction

The hybrid organic-inorganic lead halide perovskites (HOIPs), which chemical formula is ABX$_3$, (the A-site is occupied by a small organic cation, (e.g., CH$_3$NH$_3^+$, CH$_3$(NH$_2$)$_2$) and MA$^{+}$, FA$^{-}$ for short.), while B-site is a divalent metal (e.g., Ge$^{2+}$, Sn$^{2+}$, or Pb$^{2+}$) and the X-site is a halogen (e.g., Cl$^-$, Br$^-$, I$^-$) show extraordinary application potentials in light-emitting diodes (LEDs) [1], lasers [2], photodetectors [3] and solar cells [4, 5] on account of their excellent photoelectric characteristics such as direct bandgap [6], long carrier lifetime [7, 8], high photon absorption efficiency [9] and outstanding carrier diffusion ability [10]. MAPbBr$_3$ of the MAPbX$_3$ family exhibits great optical absorption ability in the visible spectra band [11, 12], which makes it highly anticipated in photodetectors [13] and light-emitting devices [14]. Furthermore, in contrast with MAPbI$_3$, MAPbBr$_3$ shows more advantages on account of chemical and thermal stability as preferred choice for optoelectronic applications in visible band.

Single crystals have significant advantages in optoelectronic device fabrication due to their lower density of inherent defects, such as surface states, different lattice orientations, and grain boundaries [15–17]. With the single crystal showing its wide potential superiorities, such as longer carrier diffusion length and lifetime, several types of single crystal photodetectors have been demonstrated, such as metal-semiconductor-metal (MSM)-type [18], Schottky-type [19], p–n/p–i–n-type [20] photodetectors and plentiful results have been obtained. However, the photodetectors above have difficulties in detecting weak signals for lacking of structure and external optimizations. Although avalanche photodiodes (APD) detectors can realize single photon detection, high requirements of material quality, fabrication arts, high operating voltage and low operating temperature...
limit their wide applications [21]. In recent years, many approaches have been developed to improve the performances of the devices [22], but high responsivity and external quantum efficiency (EQE) devices are still highly expected in this area. In this situation, SPs has been explored to obtain high-sensitivity photodetectors. Recently, the technique of SPs has been employed in many areas. For example, biosensing [23], lasers [24], nanophotonics [25], integrated optics [26] and so on. As for photodetectors, plenty of results based on III–V group materials, silicon, and two-dimensional materials have been reported. For III–V group materials, Tong et al proposed an InAsSb-based hetero-n-i-p photodiode integrated with an Au-based two-dimensional square-lattice hole array structure, which responsivity and detectivity increased about 3 times at 150 mV bias [27]. Qiu et al designed a n-InAsSb/n-GaSb heterodetector integrated with a two-dimensional metallic square-hole array, which photocurrent increased about 2 times at 1.80 μm [28]. For silicon-based device, Sobhani et al reported an n-doped silicon Schottky photodetector with an Au grating layer. The grating geometry enables around three times larger photocurrent responsivity than pristine device [29]. As a member of two-dimensional materials, graphene was applied to photoconductive type detector. Yao et al showed an end-to-end plasmonic antenna structure fabricated on a graphene sheet, which demonstrated more than 200 times enhancement of responsivity at mid-infrared band compared to devices without antennas [30]. Besides, Molybdenum disulfide (MoS2) was a novel two-dimensional material for optoelectronic devices. Miao et al deposited 4 nm thick Au nanoparticles sparsely onto few-layer MoS2 phototransistors, and observed two times increase in the photocurrent response [31]. In addition, the SPs enhanced photodetector based HOIPs thin films performances have also been reported [26, 32–36]. While single crystal related research is rarely introduced especially MSM-type photodetector based on it. By deliberate design of device morphology or configuration, photodetectors based on HOIPs single crystal can achieve preferable performance.

In this research, a MAPbBr3 single crystal based MSM-type photodetector had been successfully fabricated and systematic studies of optoelectronic performances had been conducted, which included photocurrents, responsivities, EQEs and detectivities in different conditions. Our results indicate that the SPs introduce a significant increasement of photocurrents and responsivities under different wavelength irradiation lights, and finally a suppression of ionic migration has also been observed.

2. Materials and methods

2.1. Synthesis of CH3NH3Br
CH3NH3Br was synthesized by reacting HBr (≥40%) with slight excess CH3NH2 solution (≥40%) in an ice bath in ambient atmosphere. Waiting for reaction about 6 h and then sealing the mixed solutions tightly with temperature of 60 °C for 24 h. The crystallization of CH3NH3Br was achieved by evaporation of water at 60 °C, and white CH3NH3Br powder was gradually precipitated out.
2.2. Single crystal growth
MAPbBr$_3$ single crystals were grown by unchanged temperature method [37, 38]. The unchanged temperature method was as follows: dissolving CH$_3$NH$_3$Br and PbBr$_2$ (98%) with 1:1 molar ratio in 10 ml DMF solution (99.5%) at room temperature by stirring continually. Then a 0.6 mol L$^{-1}$ transparent solution was obtained. Next step was adding a small seed crystal into the transparent solution and the solution was kept at 85$\degree$C. Large size MAPbBr$_3$ single crystals were obtained after 1–2 days. Figure 1(a) depicts the schematic diagram of the MAPbBr$_3$ single crystal growth process. By filtering the depositions from the mixed solution which was placed in constant temperature water bath at 85$\degree$C and then evaporating the saturated clarified liquid, spontaneous nucleation of grains was observed. After a few steps of disposing, large crystals of high quality can be obtained. Figure 1(b) shows the photo of a single crystal of MAPbBr$_3$ with 0.6 cm $\times$ 0.6 cm size. The corresponding XRD patterns of the MAPbBr$_3$ powder and single crystal are shown in figure 1(c).

2.3. Device fabrications
Planar photodetectors were made on (100) lattice plane of MAPbBr$_3$ single crystal. The single crystal facet was carefully polished by abrasive paper to reduce surface polycrystallinity, trap-related defects and decomposition which lead to performance reduction of optoelectronic device. The device was manufactured as soon as possible after polishing. During the Au sputtering process, the hollow aluminum contact pattern mask was put on the facet and then Au zigzag electrodes can be obtained under the blank area of the hollow aluminum mask after Au sputtering. The effective light absorption size can be calculated by the 2000 $\mu$m side length of device and the 100 $\mu$m width and separation distances of the interdigited area.

2.4. Characterizations and measurements
X-ray diffraction patterns of MAPbBr$_3$ single crystal powder were measured by a D/Max2500PC X-ray diffractometer with Cu K$_{\alpha1}$ irradiation, and the scan range was 10$^\circ$–70$^\circ$. Surface morphologies were measured using Atomic Force Microscope (AFM) in tapping mode by HORIBA AFM tester. Photoluminescence (PL) spectrum were obtained using IdeaOptics spectrometer with 375 nm continuous laser as excited light source. Time-resolved PL was acquired with a time correlated single photon counting detector (PicoQuant) with 375 nm pulse laser. The optoelectronic properties of photodetector were investigated at ambient temperature and measured by Keithley 4200 A instrument. In order to compare the influence of SPs on optoelectronic properties, the measurements were conducted in varied LD power (at fixed wavelength) and wavelength (at fixed power) respectively to test the pristine or hybrid photodetectors sequentially. The NPs were sputtered overall 2 s in the condition of $8 \times 10^{-2}$ mbar vacuum degree.
3. Results and discussion

The figures 2(a), (b) show the surface topography of pristine single crystal and corresponding 3D images. The figures 2(d), (e) show the surface topography with randomly dispersed Au NPs of hybrid single crystal and corresponding 3D images, which the average size is on the order of 100 nanometers. The device morphology and measurements configurations were shown in figures 2(c), (f). Plane MSM-type photodetector was manufactured on (100) facet of MAPbBr3 single crystal and image of surface appearance is demonstrated in figure 2(c). Au zigzag electrodes can be obtained under the blank area of the hollow aluminum mask after sputtering process. Hence, the hollow aluminum contact pattern mask area was the corresponding light absorbing area of the photodetector. Figure 2(f) illustrates the configurations for photoelectric measurements employing an electrical properties analyzer combined with a probe station. The dark current measurement was investigated in the condition of a shielding box and the photocurrents were obtained under illuminations of two different semiconductor laser diodes (LDs, 532 nm, 630 nm) as excited light sources. All the measurements were performed without and with Au NPs sequentially.

Dark current, photocurrent, responsivity, EQE and detectivity are the key parameters to evaluate the performances of photodetectors. Figure 3(a) shows the dark current and photocurrents obtained by using a 630 nm LD with different irradiation powers respectively. The dark current is as low as nanoamperimeter order of magnitude benefitting from the high crystal quality. Under laser illumination, currents exhibit a huge increase in contrast to the dark condition and the photocurrent grow up to $2.5 \times 10^{-7}$ A under 5 V bias voltage with 0.5 mW irradiation power. Photocurrents shown in figure 3(a) increase with the growth of incident light power densities as more photons can excite more electron-hole pairs contributing to the photocurrents. The photocurrent under 5 mW irradiation power to dark current ratio both in 5 V bias is 29.7. Moreover, the increase trends of photocurrents can be divided by the 0.4 V inflection point. The photocurrents increase sharply when the bias voltage is lower than 0.4 V, which can be ascribed to the exists of Au-MAPbBr3 Schottky junctions [39]. Nearly-linear curve is obtained when the bias voltage exceeds 0.4 V which can be conclude to the ohmic region [40]. Additionally, the ion migration is one of the considerable factors to suppress the increase of currents. With regard to halide perovskites, vacancies can get over lower activation energies to migrate in a hopping mode between neighboring positions when the bias increases gradually [41, 42] which introduce the cations and anions accumulate near the cathode and anode to generate a built-in electric field impeding the photocurrents increase dramatically.

Figure 3(b) depicts the dark current and photocurrents versus bias voltage in different irradiation powers at fixed 630 nm laser with Au NPs. The dark current increases for nearly an order of magnitude in contrast with the aforementioned sample and the photocurrents improve simultaneously. For instance, under 5 V voltage bias and 0.5 mW irradiation, the photocurrent reaches $5 \times 10^{-7}$ A and two times enhancement has been obtained.
compared with pristine sample. Figure 3(b) still illustrates proportional relationship between photocurrents and irradiation power and the photocurrent under 5 mW irradiation power to dark current ratio both in 5 V bias is 6.9. Whereas, the shape of curve is far different from before. Except for conventional ohmic region can be observed at lower voltage region, the $I-V$ characteristics of the single crystal change at $V_{TFL}$ and the currents show an abrupt increase implying the transition into the trap-filled limit (TFL), where the trap states are filled or trapped by charged carriers [42]. The value of inflection point $V_{TFL}$ can be calculated by the following formula:

$$V_{TFL} = \frac{eN_{\text{traps}}L^2}{2\varepsilon \varepsilon_0}$$

where $e$ is the elementary charge, $N_{\text{traps}}$ is the trap density of the crystal, $L$ is the length between the two electrodes, $\varepsilon$ and $\varepsilon_0$ stand for the dielectric constant of MAPbBr$_3$ and the vacuum permittivity respectively. The value of $V_{TFL}$ decreases with the increase of irradiation power can be easily observed from Figure 3(b). Increased irradiation power can excite more carriers to fill the traps so that the trap density of the crystal decreases. Moreover, by comparing the growth trend of photocurrents between figures 3(a) and (b) we can find that Au NPs not only enhance the photocurrents response, but also prevents the effect of ion migration on photocurrents. The Au NPs structures located on the surface of crystal suppress ion migration which mainly occurs on the surface of the single crystal.

The responsivity $R$, EQE, and detectivity ($D$) can be calculated by the following formula:

$$R = \frac{I_{ph} - I_{dark}}{P_{irr} \times S_{eff}}$$

$$\text{EQE} = \frac{R \times h\nu}{e \times \lambda}$$

$$D = \frac{R}{(2e \times I_{dark})^{1/2}}$$

where $I_{ph}$ and $I_{dark}$ are photocurrents and dark current. $P_{irr}$ is irradiation light power density, and $S_{eff}$ is the effective area of the detector, $h$ represents the Planck constant and $c$ is the speed of light. $\lambda$ indicates the wavelength of incident light. Responsivity refers to the ratio of the output signal of a photodetector to the light power, which is the main parameters of devices performances to evaluate and depict the photoelectric conversion ability of photodetector. EQE presents the ability of the device to convert the number of photons from the incident light to the number of carriers flowing into the external circuit. $D$ represents the detection level of the detector. As the incident laser wavelength is fixed at 630 nm and the irradiation power is varied from 0.1 mW to 0.5 mW, the responsivities and EQEs of single crystal photodetector without or with Au NPs are...
shown in figure 3(c), d respectively. We can obviously infer that the responsivities and EQEs rely on the bias voltages and illumination powers which are positively correlated with the bias. The shapes of these two illustrations are very similar to the trend of former I–V characteristics. For the detailed numerical results, the highest value of responsivity and EQE in figure 3(c) are $1.7 \times 10^{-3}$ AW$^{-1}$ and 0.22% respectively under 5 V bias and 0.1 mW. In addition, the highest value of responsivity and EQE with Au NPs in figure 3(d) are $2.4 \times 10^{-3}$ AW$^{-1}$ and 0.37% respectively, at the same condition. Compared to the maximum responsivity and EQE of MSM photodetector without Au NPs, an enhancement of 41% and 68% has been obtained respectively.

By further increasing the irradiation power, both responsivity and EQE start to decrease. Figure 3(e) shows that the D start to decrease when the voltage exceeds 0.5 V which indicates the instability of the device when facing high voltage applied. However, the detector modified with Au NPs shows outstanding stability even when the voltage exceeds 2.5 V exhibiting in figure 3(f). Which also proves implicitly that surface Au structures can improve the detector's stability by suppressing the ionic migration. The relevant data comparison of pristine and hybrid photodetectors are shown in table 1.

Table 1. Relevant parameters ratio of photodetector with and without NPs.

| Laser output power (mW) | Maximum current ratio$^a$ | Maximum responsivity ratio$^b$ | Maximum EQE ratio$^c$ | Maximum detectivity ratio$^d$ |
|-------------------------|---------------------------|---------------------------------|-----------------------|------------------------------|
| Dark                    | 9.05                      | \_                              | \_                    | \_                           |
| 0.1                     | 2.14                      | 1.73                            | 1.73                  | 0.66                         |
| 0.2                     | 2.08                      | 1.72                            | 1.72                  | 0.69                         |
| 0.3                     | 2.10                      | 1.79                            | 1.79                  | 0.54                         |
| 0.4                     | 2.12                      | 1.86                            | 1.86                  | 0.67                         |
| 0.5                     | 2.09                      | 1.84                            | 1.84                  | 0.69                         |

$^a$ Means maximum current value with NPs is divided by that without NPs.

$^b$ Means maximum responsivity value with NPs is divided by that without NPs.

$^c$ Means maximum EQE value with NPs is divided by that without NPs.

$^d$ Means maximum detectivity value with NPs is divided by that without NPs.

In order to study the response of photodetector with Au NPs to different light wavelengths, we used 630 nm and 532 nm laser (all the lasers above were fixed at same output power) to illuminate (100) lattice plane of the device. Figure 4(a) depicts the photocurrents of pristine device under two different wavelength illuminations. The photocurrent response of the device to 630 nm LD shows slightly inferior, which the highest value is about $2.3 \times 10^{-7}$ A at 5 V bias. The orange MAPbBr$_3$ single crystal inclines to reflect rather than absorbing 630 nm wavelength photons is the reason why the photocurrent under red light irradiation shows insensitivity in contrast with other two wavelengths. The photocurrent illuminated by 532 nm laser is around $2.2 \times 10^{-5}$ A under 5 V bias. Besides, the device under 532 nm laser irradiation performs higher current response than other laser is due to the resonance absorption as the photon energy consistent with the value of $E_g$ of MAPbBr$_3$ single crystal reported before [38]. Furthermore, we can see the increase rates of the two curves are still limited by the ion migration. Figure 4(b) reveals the photocurrents response of the device with Au NPs under two different wavelengths. Compared with figure 4(a), the photocurrents show distinct increasement tendency with
improved bias. Taking the detailed numeric results into account, the maximum currents under two different laser illuminations are $4.5 \times 10^{-7}$ A and $2.8 \times 10^{-5}$ A respectively. Compared to the reference device without Au NPs, 112% and 26% enhancement in maximum photocurrent are observed. The reason why the response under two laser irradiations grow significantly will be discussed in the following section. The responsivities and EQEs of the devices under two different irradiation wavelengths without and with Au NPs are shown in figures 4(c) and (d). The results are approximately the same as the photocurrents. As the highest values of responsivities and EQEs without Au NPs are $5 \times 10^{-4}$ A W$^{-1}$ and 0.07%, $5.8 \times 10^{-2}$ A W$^{-1}$ and 14% respectively. In terms of the highest values of responsivities and EQEs with Au NPs are $5.2 \times 10^{-4}$ A W$^{-1}$ and 0.08%, $7 \times 10^{-2}$ A W$^{-1}$ and 16%. For D shown in the figures 4(e) and (f), one can see that the Au NPs response sensitively to the 532 nm laser, and D increase gradually compared to 532 nm curves which indicates that the modified Au NPs tend to improves the detector’s ability in detecting 630 nm photons and the stability when facing device degradation caused by ionic migration as the increased bias. The relevant data comparisons of photodetector with and without Au NPs are shown in table 2.

The photocurrents enhancement in device are primarily ascribed to the electrical effects of Au SPs play a pivotal part in promoting the charge extraction and transport. The pristine MAPbBr$_3$ single crystal exhibited a PL peak at around 532 nm with the excitation wavelength of 375 nm. With the introduction of Au NPs, drastic PL quenching was observed as presented in figure 5(a), implying that the excited electrons in MAPbBr$_3$ probably transfer to Au NPs by reducing the charge recombination [43]. The decrease in PL lifetime for the hybrid single crystal also validates the effective electron transfer process between perovskite and Au NPs as proved by time-resolved PL measurements (figure 5(b)). Notably, when Au NPs are directly attached to the Au electrodes and contacted with the perovskite, the photon-generated carriers in the perovskite can be extracted to the Au electrodes through the Au NPs under illumination, causing the carrier collection efficiency increased [44].

### 4. Conclusions

In summary, we have investigated the enhancement of performances on planar MSM photodetectors based on MAPbBr$_3$ single crystal with sputtered Au NPs by measuring and calculating photocurrent, responsivity, EQE and detectivity. By comparing with the device without Au NPs using different incident light powers or wavelengths, photocurrents, responsivities, and EQEs all displayed a certain of improvements. Additionally, the Au SPs not only enhanced the performances parameters, but also suppress the ion migration of the MAPbBr$_3$ crystals by reducing the trap states. This phenomenon is particularly evident for device with NPs under 630 nm wavelength light sources. The study on the perovskite with SPs establish a scope for developing further fundamental knowledge and practical applications of perovskite-based especially single crystal optoelectronic and electronic devices.

### Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Grant 51702186); Key R&D Project of Shandong Province (Grant 2018GGX101033); National Key R&D Program of China (Grant 2016YFB0401802-); Young Scholars Program of Shandong University.

### ORCID iDs

Zhiyuan Zuo  [https://orcid.org/0000-0002-3261-9217](https://orcid.org/0000-0002-3261-9217)
References

[1] Tan Z-K et al 2014 Nat. Nanotechnol. 9 687–92
[2] Zhu H M, Fu Y P, Meng F, Wu X X, Gong Z Z, Ding Q, Gustafsson M V, Trinh M T, Jin S and Zhu X Y 2015 Nat. Mater. 14 636–42
[3] Ding J X, Du S J, Zhao Y, Zhang X J, Zuo Z Y, Cui H Z, Zhan X Y, Gu Y J and Sun H Q 2017 J. Mater. Sci. 52 276–84
[4] Nie W Y, Blancon J C, Neukirch A J, Appavoo K, Tsai H, Chhowalla M, Alam M A, Steir M Y, Katan C and Even J 2016 Nat. Commun. 7 11574
[5] Elumalai N K and Uddin A 2016 Energy Mater. Sol. Cells 157 476–509
[6] Xing G C, Mathews N, Sun S Y, Lim S S, Lam Y M, Grätzel M, Mhaisalkar S and Sum T C 2013 Science 342 344–7
[7] Dong Q F, Fang Y J, Shao Y C, Mulligan P, Qiu J, Cao L and Huang J S 2015 Science 347 967–70
[8] Saidaminov M I, Abdelhady A L, Murrali B, Alarousu E, Burlakov V M, Peng W, Dursun I, Wang L F and He Y 2015 Nat. Commun. 6 7856
[9] Green M A, Ho-Ballie A and Snaith H J 2014 Nat. Photonics 8 506–14
[10] Stranks S D, Eperon G E, Grancini G, Menelaou C, Alcocer M J P, Leijtens T, Herz L M, Petrozza A and Snaith H J 2013 Science 342 341–4
[11] De W S, Holovsky J, Moon S J, Loper P, Niesen B, Ledinsky M, Haug F J, Yum J H and Ballal C 2014 J. Phys. Chem. Lett. 5 1035–9
[12] Maculan G, Sheikh A D, Abdelhady A L, Saidaminov M I, Haque M A, Murrali B, Alarousu E, Mohammed O F, Wu T and Bakr O M 2015 J. Phys. Chem. Lett. 6 3781–6
[13] Fang Y J, Dong Q F, Shao Y C, Yuan Y B and Huang J S 2015 Nat. Photonics 9 679–86
[14] Xiao Z G, Kerner R A, Zhao L F, Tran N L, Lee K M, Koh T W, Gregory D S and Barry P R 2017 Nat. Photonics 11 108–15
[15] Yang D, Yang R X, Zhang J, Yang Z, Liu S Z and Li C 2015 Energy Environ. Sci. 8 3208–14
[16] Unger E L, Hoke F T, Ballal C D, Nguyen W H, Boewing A R, Heumuller T, Christoforo M G and McGeehe M G D 2014 Energy Environ. Sci. 7 3699–80
[17] Snaith H J, Abate A, Ball M J, Eperon G E, Leijtens T, Noel N K, Stranks S D, Wang T W, Wojciechowski K and Zhang W 2014 J. Phys. Chem. Lett. 5 1511–5
[18] Walker D, Monroy E, Kung P, Wu J, Hamilton M, Sanchez F J, Diaz J and Razeghi M 1999 Appl. Phys. Lett. 74 762–4
[19] Atalilla M, Jiang Z Y, Liu J, Wang L, Ashok S and Xu J 2015 J. Appl. Phys. 117 134503
[20] Brennan K F 1987 IEEE. T. Electron Dev. 34 1658–69
[21] Wu Y, Sun X J, Jia Y P and Li D B 2018 Chin. Phys. B 27 126101
[22] Li D B, Jiang K, Sun X J and Guo C L 2018 Adv. Opt. Photon. 10 43–110
[23] Homola J 2008 Chem. Res. 108 462–93
[24] Berini P and Leon J D 2012 Nat. Photonics 6 16–24
[25] Barnes W L, Dereux A and Ebbsen T W 2003 Nature 424 824–30
[26] Ebbsen T, Genet C and Bozhevolnyi S 2008 Phys. Today 61 44–50
[27] Tong J C, Tobing L Y M, Qiu S P, Zhang D H and Unil Perera A G 2018 Appl. Phys. Lett. 113 011110
[28] Qiu S P, Tobing L Y M, Tong J C, Xie Y Y and Yu Z J 2016 Opt. Quant. Electron. 48 203
[29] Sobhani A, Knight M W, Wang Y M, Zheng B and King N S 2013 Nat. Commun. 4 1643
[30] Yao Y, Shankar R, Rauter F, Song Y and Kong J 2014 Nano Lett. 14 3749–54
[31] Miao J S, Hu W D, Jing Y L, Luo W J, Liao L, Pan A L, Wu S W, Cheng X J, Chen X S and Lu W 2015 Small 11 2392–8
[32] Hu X, Zhang X D and Liang L 2014 Adv. Funct. Mater. 24 7373–80
[33] Zhou S F, Zhang F E, Shi Y M, Huang Y and Zhang B 2015 Angew-Chem-Int. Edit. 54 5693–6
[34] Chen K and Tüysüz H 2015 Angew-Chem-Int. Edit. 54 13806–10
[35] Liu C, Wang K, Yi C, Shi X J, Du P C, Smith A W, Karima A and Gong X 2015 J. Mater. Chem. C 3 6600–6
[36] Sun Z H, Aigouy L and Chen Z Y 2016 Nanoscale 8 7377–83
[37] Ding J X, Zhao Y, Du S J, Sun Y S, Cui H Z, Zhan X Y, Cheng X H and Lin J 2017 J. Mater. Sci. 52 7907–16
[38] Zuo Z Y, Ding J X, Zhao Y, Du S J, Li Y F, Zhan X Y and Cui H Z 2017 J. Phys. Chem. Lett. 8 684–9
[39] Deng H, Yang X K, Dong D D, Li B, Yang D, Yuan S J, Qiao K K, Cheng Y B, Tang J and Song H S 2015 Nano Lett. 15 7963–9
[40] Eames C, Frost I M, Barnes P R F, Regan B C O’, Walsh A and Islam M S 2015 Natue Comm 6 4977
[41] Bube R H 1962 J. Appl. Phys. 33 1733–1737
[42] Schulz P, Edri E, Kirmayer S, Hodes G, Cahan D and Kahn E 2014 Energy Environ. Sci. 7 1377–81
[43] Wang H, Lim J W, Quan L N, Chung K, Jang Y J, Ma Y and Kim D H 2018 Adv. Opt. Mater. 6 1701397
[44] Baek S W, Kim J H, Kang J, Lee H, Park J Y and Lee J Y 2015 Adv. Energy Mater. 5 1501393