Colloidal InSb Quantum Dots/Organic Integrated Bulk Heterojunction for Fast and Sensitive Near-Infrared Photodetectors

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It remains urgent to integrate conductive InSb colloidal quantum dots (CQDs) for sensitive and fast near-infrared (NIR) photodetection applications. Herein, nanocrystallized InSb CQDs (\(<12\) nm in diameter) have been successfully obtained via hot-injection procedure, and demonstrated a very narrow absorption peak centered at \(1406\) nm with a full width at half maximum (FWHM) of \(10.3\) nm and a broader absorption peak at \(1702\) nm, indicating strong quantum-confined effect. After integrating these InSb CQDs with \([6,6]\)-phenyl \(C_60\)-butyric acid methyl ester (PCBM) and polymeric triphenyldiamine (poly\((N,N'\)-diphenylbenzidine diphenylether), poly-TPD) bulk junction, the obtained Si/SiO\(_2\)/InSb CQDs: PCBM:poly-TPD/Ag photodetector has reached long-wavelength response up to \(1400\) nm, fast response time (\(<80\) ms), and superior on/off ratio. In specific, charge carriers can be effectively transported due to favorable energy alignment and interpenetrating network formed in the inorganic/organic blend films. The work provides a new strategy to synthesize high-quality InSb CQD and reveal its starting point toward low-cost, practical, and sensitive next-generation NIR detection.

1. Introduction

Photodetector, a device that detects light and transforms it into electrical signal, has been widely applied in the field of optoelectronics for various purposes, such as remote imaging,\(^{[1–3]}\) space exploration,\(^{[4,5]}\) environment monitoring,\(^{[6,7]}\) and telecommunication.\(^{[8–10]}\) Though the commercial silicon-based photodetector shows excellent performance, its detecting ability is limited to UV and visible light range due to its wide bandgap of \(1.1\) eV.\(^{[11–14]}\) To extend near-infrared (NIR) detection, conventional III–V compounds such as InGaAs,\(^{[15,16]}\) InSb,\(^{[17,18]}\) InAsSb\(^{[19]}\) as well as epitaxial superlattice materials\(^{[20,21]}\) have been primarily explored for high-speed electronic and efficient optoelectronic devices. However, their devices suffer from various technical challenges including mechanical inflexibility, complicated, and expensive manufacturing processes. These traditional inorganic devices usually need sophisticated operating requirements such as low temperature and pressure, which limit their ordinary use in flexible, portable, and low-cost infrared devices.\(^{[22]}\) Therefore, it is in great need to develop cheap and lightweight infrared products to accelerate the development of next-generation integrated optoelectronics. Owing to the advantages of great chemical functionalization capability, tailorable optoelectronic properties, and solution processability of InSb colloidal quantum dot (CQD), it has received great attention as one of the suitable new materials to realize NIR photodetectors. It is noteworthy that colloidal synthesis methods hold enormous potential to fabricate low-cost and solution-processed optoelectronic devices.
Unfortunately, the strong covalent nature of atomic bonding in bulk InSb causes extreme difficulties in InSb CQD synthesis, requiring high-temperature processes, long reaction time, and highly reactive precursors. The highly reactive precursors play a critical role in promoting the reaction, whereas the rapid reaction process could result in uncontrollable morphology and undesirable nanocrystalline size of the final product. Therefore, the lack of suitable precursors to provide In and Sb sources has resulted in synthetic challenges of high-quality InSb CQDs. So far, there are only very few reports about InSb CQDs preparation and their integration for efficient optoelectronic devices. In 2019, Liu et al. first reported InSb CQDs synthesis by employing a Sb[Na(Si(Me)3)2]3 as precursor, and achieved ambipolar charge report in their resulting InSb CQDs-based field-effect transistor device. Archana et al. synthesized InSb CQDs with few Sb impurity by solvothermal self-reduction method, successfully extending the light absorption range to the NIR regime. Moreover, accessible InCl3 and pnictogen chlorides (PnCl3, Pn = As and Sb) have been exploited to synthesize size- and stoichiometry-tunable binary InAs and InSb, and their ternary alloy InAs1−xSbx CQDs field-effect transistors demonstrated short wavelength infrared photoresponse through size and composition control. Yet, very weak photoresponse is achieved for the InAs CQDs-based photodetector. Krylsky et al. reported large-sized InSb CQDs (~20 nm), but their devices have barely shown obvious photoresponse. Efforts remain to further develop InSb CQD-related optoelectronics in combination with materials and device optimization engineering.

Herein, we report the successful synthesis of InSb CQDs by developing a hot-injection method using InCl3 and SbCl3 as two reactive precursors. X-ray diffraction (XRD) and transmission electron microscopy (TEM) with energy dispersive X-ray spectroscopy (EDS) mapping are employed to characterize the crystallinity and microscopic structure of InSb CQDs. The absorption peaks centered at 1406 and 1702 nm are shown in the UV–NIR regime to the NIR regime. Moreover, accessible InCl3 and pnictogen chlorides (PnCl3, Pn = As and Sb) have been exploited to synthesize size- and stoichiometry-tunable binary InAs and InSb, and their ternary alloy InAs1−xSbx CQDs field-effect transistors demonstrated short wavelength infrared photoresponse through size and composition control. Yet, very weak photoresponse is achieved for the InAs CQDs-based photodetector. Krylsky et al. reported large-sized InSb CQDs (~20 nm), but their devices have barely shown obvious photoresponse. Efforts remain to further develop InSb CQD-related optoelectronics in combination with materials and device optimization engineering.

2. Experimental Section

2.1. InSb CQDs Synthesis and Purification

The InSb CQDs were synthesized through hot-injection method with commercial InCl3 and SbCl3 powder as reactive precursors; a schematic diagram of the InSb CQD synthesis process is shown in Figure 1a. In the first step, 194 mg InCl3 and 200 mg SbCl3 powders were added in 2 mL toluene, followed by stirring to obtain InSb CQD precursor. At the same time, 10 mL oleylamine in three-necked bottle was heated with dropping of 0.7 mL 2.0 M super-hydride solution (SH) at 240 °C, and the color of solution turned yellow after SH addition. Therein, 2.0 M SH was prepared by mixing 1.0 M LiEt3BH in tetrahydrofuran (THF) and half volumes of diocetyl ether, and then degassing the mixture at room temperature in a Schlenk line under reduced pressure until the THF is completely removed. To note, LiEt3BH should be handled in air-free condition because of its high reactivity in air. Then, 0.25 mL InSb precursor was injected to the three-necked bottle, and the color of solution briefly turned brown and then black with holding reaction time of 8 min. The solution was transferred to a vial containing 6 mL toluene to quench the reaction immediately. After the reaction solution was cooled down to room temperature, 1 mL oleic acid (OA) was added in the bottle to neutralize excess SH, and OA was attached to the surface of the CQDs to improve product’s stability. Finally, crude solution was centrifuged at 3000 rpm for 10 min to remove the insoluble by-products, and then methyl alcohol and butyl alcohol were added in the same volume to supernatant. This mixture was purified through centrifugation at 8000 rpm for 10 min to get precipitates which were then dissolved in 5 mL toluene. The final InSb CQDs to fabricate device were obtained after repeating the purified processes for three times.

2.2. Device Fabrication

Before fabrication, the Si/SiO2 substrate was ultrasonically cleaned by acetone, ethyl alcohol, deionized water, and treated by UV-ozone. Then, 10 μL solution for active layer was spin-coated on Si/SiO2 substrate at 3000 rpm for 30 s, followed by thermal annealing at 110 °C for 1 h in N2 glove box. Finally, 300 nm-thick Ag electrodes were deposited by thermal evaporation under 5 × 10−4 Pa with a deposition rate of 2 Å s−1.

2.3. Characterizations of InSb CQDs

Crystal structure of the as-synthesized InSb CQDs was determined on a desktop diffractometer (D8 Advance, Bruker, Germany) with a Cu Kα source at the range of 15°–80° (D8 Advance; Bruker, Germany). The absorption spectrum was recorded at room temperature in the range of 800–2000 nm by a UV–vis spectrophotometer (Cary 5000 UV–vis–NIR, Agilent, USA). Micromorphology was observed by high-resolution transmission electron microscopy (HR-TEM, JEM-3200FS) equipped with EDS. Ultraviolet photomission spectroscopy (UPS) spectra were collected using an Omicron ultrahigh vacuum system with a base pressure of 2.6 × 10−10 mbar.
2.4. Device Characterizations

Channel length and width of device were obtained through optical microscopy. The current–voltage (I–V) and current–time (I–t) curves measurements were carried out with a home-made system at room temperature which consisted of probe, Keithley 2600B source meter, a continuous wavelength tunable light source from 430 to 1450 nm (YSL SC-PRO 7 and AOTF-PRO).

3. Results

The X-ray diffraction (XRD) patterns of the final products are shown in Figure 1b. The strong and sharp reflection peaks can be indexed to the typical peaks of (111), (220), (311), and (422) for the cubic InSb (JCPDS card no. 73-1985), indicating pure InSb CQDs with high crystallinity have been obtained. The absorption spectrum of as-obtained InSb CQDs solution in Figure 1c shows a narrow absorption peak centered at 1406 nm with a full width at half maximum (FWHM) of 10.3 nm as the smallest in infrared region and a broad absorption peak at about 1702 nm, respectively, indicating strong quantum-confined size effect. The inset of Figure 1c is a photo of the synthesized product. Moreover, Figure 1d,e show that the absorption peak at 1406 nm remains even when the reaction time increases from 8 to 150 min or the precursor content reduces from 0.5 to 0.125 mL, indicating the existence of the magic sized cluster (MSC-1406) of obtained InSb CQDs which is critical state for...
further CQDs nucleation and growth. The peak at 1700 nm (QD-1700) becomes gradually weaker, and eventually disappears when the reaction time is 150 min and precursor content is 0.125 mL, which is related to the final InSb CQDs. Meanwhile, the amount of precursor could be further optimized to 0.25 mL to reach the adequate synthesis of InSb CQDs when the amount of the super-hydride solution is fixed as shown in Figure 1e, resulting in the strongest absorption intensity both at 1406 and 1700 nm. And the coexisting solution of MSC-1406 and QD-1700 can be separated using centrifugation treatment as shown in Figure S1, Supporting Information.

TEM image in Figure 2a confirms that the uniform InSb CQDs have been obtained with a size range of 4.4 and 11.6 nm (Figure 2b). The HR-TEM image indicates the lattice spacing of 0.195 and 0.374 nm (corresponding to the (311) and (111) planes of the InSb, respectively (Figure 2c), which is consistent with the XRD results of Figure 1b. The elemental composition of the synthesized InSb CQDs was investigated by EDS; the In/Sb atomic ratio is approximately 1:1 (Figure S2, Supporting Information), which is consistent with XRD results. Figure 2d,e,f shows the EDS mappings of In, Sb, and overlapped elements, respectively. The uniform distribution of In and Sb elements marked with red and green dots indicates homogeneous InSb CQDs.

The schematic illustration of photodetector with a structure of Si/SiO₂/InSb CQDs:PCBM:poly-TPD/Ag is shown in Figure 3a, and the optical image of device with the channel length of 110 μm and width of 30 μm is shown in Figure S3, Supporting Information. Figure 3b shows the corresponding $I-V$ curves of the device without and with InSb CQDs in dark and under laser excitation of 800 nm. Device using InSb CQDs:PCBM:poly-TPD as active layer has higher photocurrent compared with device without InSb CQDs, indicating obvious photoresponse from InSb CQDs. Specifically, the photocurrent is about two orders of magnitude higher than the dark current of device with InSb CQDs. Under the periodic on/off laser excitation of 800 nm, the current–time relationship of photodetector with InSb CQDs:PCBM:poly-TPD as the active layer is shown in the inset of Figure 3c. The regularly rectangular current–time diagram demonstrates the steady and sensitive light response. Moreover, the response time refers to the time required of current changing between the maximum and minimum under on/off light, reflecting device response speed. As shown in Figure 3c, the corresponding response time including rise and decay time of our device is shorter than the instrument test.

Figure 2. a) TEM image and b) size distribution of InSb sample. c) HR-TEM image and lattice spacing analysis of InSb CQDs sample. EDS elemental mapping characterization of d) In, e) Sb, and f) overlapped elements.
limitation of 80 ms, indicating fast photoresponse. In contrast, the device fabricated with PCBM:poly-TPD organic blend film as the active layer shows weak photoresponse with 800 nm laser excitation as shown in Figure 3b. In the meantime, the rise time dramatically increases to 830 ms, indicating slow response as shown in Figure 3d. At the same time, without PCBM and poly-TPD, the device with pure InSb CQDs has exhibited no response due to the high potential barrier built up between CQDs and metal electrode, limiting carrier collection in Figure S4, Supporting Information. There, the as-prepared pure InSb CQDs photodetector shows almost no photoresponse, indicating that InSb CQD only could not make a good or effective junction with metal contact for photodetectors application. It does not have energy favorable alignment for the photogenerated holes from InSb CQDs to transport to Ag electrode. Therefore, it is critical to construct this unique InSb CQDs:PCBM:poly-TPD ternary film for effective NIR photoresponse because the integrated poly-TPD can be used as a hole transport material and PCBM:poly-TPD formed bulk junction to suppress leakage current, while InSb CQDs can mainly play their roles for NIR absorption. Figure S5a, Supporting Information, shows the champion on/off ratio of photodetector fabricated by the InSb CQDs:PCBM:poly-TPD as active layer at 800 nm, indicating the necessity of the blended ternary active layer. Even though the similar absorption intensity at 800 nm for PCBM:poly-TPD and InSb CQDs:PCBM:poly-TPD (Figure S5b, Supporting Information).

Furthermore, the device response in NIR region was measured from 800 to 1400 nm. Figure 4a shows the $I$–$t$ curves under 1000, 1200, and 1400 nm. The obvious current fluctuations caused by laser on/off indicate photovoltaic response to NIR light. Specifically, the responsivity ($R$) and detectivity ($D^*$) are the quantifiable indices to exhibit detection capability of photodetector.[10] The value of these parameters can be calculated by following formulas

$$R = \frac{I_{\text{light}} - I_{\text{dark}}}{PA}$$

$$D^* = \frac{R}{\sqrt{2I_{\text{dark}}/A}}$$

where $I_{\text{light}}$ and $I_{\text{dark}}$ indicate light and dark current, respectively. $P$ and $A$ correspond to the power density of excitation light and channel effective area, respectively. As shown in Figure 4b, the wavelength-dependent value of $R$ and $D^*$ in the range of 800–1400 nm was measured at constant power value of 0.22 mW. The changing trends of $R$ and $D^*$ value with wavelength are basically the same, and $R$ and $D^*$ reach values of 0.04 mA W$^{-1}$ and 1.5 x 10$^6$ Jones under excitation of 1400 nm respectively, which indicates that the photodetector is sensitive to infrared light. Furthermore, the power-dependent performance of device under 1400 nm excitation was measured. Figure 4c shows the photocurrent increases with the excitation power, and the relationship of photocurrent and excitation power...
can be fitted by a linear equation with $R^2$ of 0.97. This indicates efficient photogenerated charges transfer and extraction in the active layer until saturated absorption, and a mass of carrier recombination could be restrained due to passivated surface defects of CQDs by organic molecules. Power-dependent values of $R$ and $D^*$ are shown in Figure 4d. With an increase of excitation power, both $R$ and $D^*$ decrease, and the maximum values of $R$ and $D^*$ are up to 0.4 mA W$^{-1}$/C0.4 and 1.5 $\times$ 10$^6$ Jones at the power of 0.02 mW, respectively. In summary, the as-synthesized InSb CQDs show robust absorption of NIR light and the fabricated photodetectors with InSb CQDs:PCBM:poly-TPD as active layer exhibit obvious response to NIR light from 800 to 1400 nm, indicating broad photoresponse.

4. Discussion

There are very few studies on InSb CQDs-based devices, including solar cell,[28] field-effect transistor (FET)[27,31], and photodetector.[29] Even $R$ and $D^*$ values which are basic indices to show detection capability of photodetector are rarely reported. Thus, the on/off ratio is used as the key indicator for performance comparison. The photodetector fabricated using blend of as-synthesized InSb CQDs:PCBM:poly-TPD as active layer with absorption spectrum shown in Figure 5a and their device shows superior on/off ratio by one order of magnitude compared with previous reports employing InAs, InAs$_{0.5}$Sb$_{0.5}$, and InSb CQD systems (Figure 5b).[27,29,31] Generally, the low on/off ratio of photodetector based on InSb CQDs originates from inefficient charges transfer and extraction caused by unstable and nonconductive InSb CQDs, which could be easily oxidized in air. Also, due to the strong covalent feature of InSb, it is less effective to passivate surface defects through ligand engineering compared with II–VII or IV–VII nanocrystals. In our work, we have applied general oleylamine ligands to maintain stability and avoid oxidation of InSb CQDs. Moreover, effective exciton separation and carrier transfer in the device have been promoted by adopting organic blend approach instead of ligands engineering. Here, the high quality of as-synthesized InSb CQDs and the ternary blend of the active layer with idealized energy-level alignment are chosen to obtain the improved photoresponse in our work. The introduction of organic molecules not only passivates the surface defects of InSb CQDs, but also prevents them from being oxidized by air.

UPS combined with absorption spectra are used to determine the energy levels of InSb CQDs, and the Fermi level and valence band edge can be obtained, respectively, through high and low binding energy cutoff in UPS which reflects occupied electronic states.[32,33] The energy level of conduction band can be calculated with the electronic transition gap. The Fermi-level energy ($E_{\text{Fermi}}$) and its difference ($\Delta$) comparing to the valence band energy of InSb CQDs are $-4.71$ and $0.51$ eV, respectively (Figure 5c). Regarding the relationship of $E_{\text{valence band}} = E_{\text{Fermi}} - \Delta$,[34] the valence band energy of InSb CQDs is $-5.22$ eV. Moreover, the position of absorption peak centered at approximately 1406 nm reflects a bandgap of 0.89 eV, corresponding to about 6 nm quantum dots for the direct bandgap InSb semiconductor; thus, the conduction band energy of InSb CQDs is 4.33 eV. Using the energy-level values of PCBM...
and poly-TPD published in literatures, a schematic band diagram of photodetector using blend of InSb CQDs:PCBM:poly-TPD as the active layer under light excitation is depicted in Figure 5d. In our developed device, InSb CQDs are the main source of carriers due to their efficient light absorption capability; therefore, the energy levels of poly-TPD:PCBM and InSb CQDs are shown in overlapping and a single column, respectively, where effective charges carrier generation and transport could occur with an interpenetrating network formed in the blended ternary film.\[^{35–37}\] Specifically, the photogenerated electrons transit from InSb CQDs to Ag electrode, the photogenerated holes transit from valence band of InSb CQDs to HOMO of poly-TPD, and then reach to the Ag electrode on the other side. It is to note that poly-TPD can improve the obtained InSb/organic blend thin film quality, and the introduction of the PCBM with HOMO level as low as −6.1 eV can suppress the leakage current.\[^{37,38}\] Further efforts are required to improve the charges collection efficiency through improving carrier mobility in InSb CQDs solids, suppressing nonradiative recombination, and optimizing hybrid device architecture.

## 5. Conclusion

In summary, we developed a novel solution-processed method to synthesize the InSb CQDs successfully. The advantages of the integrated InSb CQDs/organic bulk heterojunction for fast and sensitive NIR photodetectors can be summarized as follows: 1) InSb CQDs without any Pb, Cd, or As toxic elements are environmentally friendly, and are beneficial for clean and healthy society; 2) the solution synthetic method is really facile and it does not need high vacuum or high-temperature conventional semiconductor manufacturing tools and can reduce the device fabrication cost significantly; 3) also it can be adopted for flexible substrate by thin film deposition in the field of wearable device; and 4) most importantly, it can extend the photoresponse to NIR wavelength region, without any complicated cooling step as required by conventional inorganic NIR photodetectors, which will significantly impact future applications of CQDs NIR photodetectors. The InSb CQDs:PCBM:poly-TPD device exhibits obvious photoelectrical response at the NIR wavelength range with the fast response. The responsivity and detectivity are up to ≈0.4 mA W\(^{-1}\), \(1.5 \times 10^6\) Jones with response time of <80 ms, respectively. More importantly, the on/off ratio of the obtained InSb CQDs photodetectors have demonstrated one order of magnitude enhancement compared with other related III–V compound CQDs system. Our work provides a pioneering strategy to synthesize InSb CQDs and reveal its potential at the field of NIR photodetectors.

## Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.
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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

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[1] T. Rauch, M. Böberl, S. F. Tedde, J. Fürst, M. Kovalenko, V. G. Hessel, U. Lemmer, W. Heiss, O. Hayden, Nat. Photonics 2009, 3, 332.
[2] X. Tang, M. M. Ackerman, M. Chen, P. Guyot-Sionnest, Nat. Photonics 2019, 13, 277.
[3] D. Shin, F. Xu, D. Venkatraman, R. Lussana, F. Villa, F. Zappa, V. K. Goyal, F. N. C. Wong, J. H. Shapiro, Nat. Commun. 2016, 7, 12046.
[4] Z. Lou, G. Shen, Adv. Sci. 2016, 3, 1500287.
[5] O. Ostroverkhova, Chem. Rev. 2016, 116, 13279.
[6] C. M. Nguyen, J. Mays, D. Plesa, S. Rao, M. Nguyen, J. Chiao, in Wireless sensor nodes for environmental monitoring in Internet of Things, 2015 IEEE MTT-S International Microwave Symposium, Institute of Electrical and Electronics Engineers (IEEE), Phoenix, Arizona, USA, May 2015, pp. 1–4.
[7] Z. Ren, J. Sun, H. Li, P. Mao, Y. Wei, X. Zhong, J. Hu, S. Yang, J. Wang, Adv. Mater. 2017, 29, 1702055.
[8] C. Xie, F. Yan, Small 2017, 13, 1701822.
[9] F. H. L. Koppens, T. Mueller, P. Avouris, A. C. Ferrari, M. S. Vitiello, M. Polini, Nat. Nanotechnol. 2014, 9, 780.
[10] L. Vicarelli, M. S. Vitiello, D. Coquillat, A. Lombardo, A. C. Ferrari, W. Knap, M. Polini, P. Vellegrini, A. Tredicucci, Nat. Mater. 2012, 11, 865.
[11] S. Mirdha, D. Basak, J. Appl. Phys. 2007, 101, 083102.
[12] G. Yu, K. Pakbaz, A. J. Heeger, Appl. Phys. Lett. 1994, 64, 3422.
[13] Z. Yu, M. Achev-Mijares, Appl. Phys. Lett. 2009, 95, 081101.
[14] X. Sheng, C. Yu, V. Malychruch, Y.-H. Lee, S. Kim, T. Kim, L. Shen, C. Horng, J. Lutz, N. C. Giebink, J. Park, J. A. Rogers, Adv. Opt. Mater. 2014, 2, 314.
[15] S. Zhao, X. Pi, C. Mercier, Z. Yuan, B. Sun, D. Yang, Nano Energy 2016, 26, 305.
[16] S. J. Xu, S. J. Chua, T. Mei, X. C. Wang, X. H. Zhang, G. Karunasiri, W. J. Fan, C. H. Wang, J. Jiang, S. Wang, X. C. Xie, Appl. Phys. Lett. 1998, 73, 3153.
[17] J. Huang, Y. Wan, D. Jung, J. Norman, C. Shang, Q. Li, K. M. Lau, A. C. Gossard, J. E. Bowers, B. Chen, ACS Photonics 2019, 6, 1100.
[18] B. W. Jia, K. H. Tan, W. K. Loke, S. Wicaksono, K. H. Lee, S. F. Yoon, ACS Photonics 2018, 5, 1512.
[19] S. Zhang, H. Xing, X. Wang, Y. Chen, H. Wang, L. Zhu, W. Jiang, J. Liu, L. Sun, T. Lin, H. Shen, W. Hu, X. Meng, D. Pan, J. Wang, J. Zhao, J. Chu, Adv. Funct. Mater. 2020, 30, 2006156.
[20] E. Delli, V. Letka, P. D. Hodgson, E. Repiso, J. P. Hayton, A. P. Craig, Q. Lu, R. Beanland, A. Krier, A. R. J. Marshall, P. J. Carrington, ACS Photonics 2019, 6, 538.
[21] Q. Durlin, J. P. Perez, L. Cerutti, J. B. Rodriguez, T. Cerba, T. Baran, E. Tournié, P. Christol, Infrared Phys. Technol. 2019, 96, 39.
[22] M. Walther, V. Daumer, F. Rutz, T. Stadelmann, V. Klinger, A. Wörli, J. Niemisz, L. Kirste, R. Rehm, Industrialization of Type-II Superlattice Infrared Detector Technology at Fraunhofer IAF, Vol. 11002, SPIE, Bellingham, WA 2019.
[23] X. Liu, Y. Lin, Y. Liao, J. Wu, Y. Zheng, J. Mater. Chem. C 2018, 6, 3499.
[24] E. Barrigón, M. Heurlin, Z. Bi, B. Monemar, L. Samuelson, Chem. Rev. 2019, 119, 9170.
[25] G. B. Stringfellow, Annu. Rev. Mater. Sci. 1978, 8, 73.
[26] Y. Kim, J. H. Chang, H. Choi, Y.-H. Kim, W. K. Bae, S. Jeong, Chem. Sci. 2020, 11, 913.
[27] W. Liu, A. Y. Chang, R. D. Schaller, D. V. Talapin, J. Am. Chem. Soc. 2012, 134, 20258.
[28] T. Archana, K. Vijayakumar, G. Subashini, A. Nirmala Grace, M. Arivanandhan, R. Jayavel, RSC Adv. 2020, 10, 14837.
[29] T. Zhao, N. Oh, D. Jishkariani, M. Zhang, H. Wang, N. Li, J. D. Lee, C. Zeng, M. Muduli, H.-J. Choi, D. Su, C. B. Murray, C. R. Kagan, J. Am. Chem. Soc. 2019, 141, 15145.
[30] L. Dou, Y. Yang, J. You, Z. Hong, W.-H. Chang, G. Li, Y. Yang, Nat. Commun. 2014, 5, 5404.
[31] D. Kryskly, V. N. D. Zhukov, Tech. Phys. Lett. 2020, 46, 901.
[32] P. R. Brown, D. Kim, R. R. Lunt, N. Zhao, M. G. Bawendi, J. C. Grossman, V. Bulovic, ACS Nano 2014, 8, 5863.
[33] J. Endres, M. Kulbak, L. Zhao, B. P. Rand, D. Cahen, G. Hodes, A. Kahn, J. Appl. Phys. 2017, 121, 035304.
[34] C.-H. M. Chuang, P. R. Brown, V. Bulovic, M. G. Bawendi, Nat. Mater. 2014, 13, 796.
[35] C. J. Brabec, A. Cravino, D. Meissner, N. S. Sariciftci, T. Fromherz, M. T. Rispens, L. Sanchez, J. C. Hummelen, Adv. Funct. Mater. 2001, 11, 374.
[36] P. Peumans, A. Yakimov, S. R. Forrest, J. Appl. Phys. 2003, 93, 3693.
[37] J. Li, J. Xia, Y. Liu, S. Zhang, C. Teng, X. Zhang, B. Liu, S. Zhao, S. Zhao, B. Li, G. Xing, F. Kang, G. Wei, Adv. Mater. Interfaces 2020, 7, 1901741.
[38] F. Huang, J. Li, Z. Xu, Y. Liu, R. Luo, S. W. Zhang, P. Nie, Y. Lv, S. Zhao, W. Su, W. D. Li, S. Zhao, G. Wei, H. C. Kuo, F. Kang, Nanomaterials 2019, 9, 1312.