Ultrabroadband Visible to Mid-wave Infrared PbS/HgTe Colloidal Quantum Dot Imagers

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Article

Keywords: Broadband, Focal plane array, Colloidal quantum dots, Multispectral imaging

Posted Date: October 5th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3372905/v1

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Abstract

Photodetection over a broad spectral range is invaluable for multispectral sensing and imaging. Despite that single-element detectors with high performance and wide spectral detection ranges have been achieved with various low-dimension materials, broadband focal plane array imagers have been rarely reported. Here, we propose a stacked PbS/HgTe colloidal quantum dot photodetector configuration with graded energy gaps, which leads to an ultrabroadband spectral response from visible to mid-wave infrared (MWIR) with excellent sensitivity and detection performance. More importantly, an ultrabroadband focal plane array imager with a resolution of 640 × 512 has been fabricated and the results show low photoresponse non-uniformity (PRNU) down to 6%. The noise equivalent temperature difference (NETD) of the broadband imager is as low as 34 mK, and high-resolution thermal images have been demonstrated. With a set of optical filters, red, green, blue, short-wave infrared, MWIR, and multispectral merged images have been captured.

Full Text

Multispectral or multi-band imaging within the visible (VIS), near-infrared (NIR), short-wave infrared (SWIR), and mid-wave infrared (MWIR) has for decades been an indispensable method in various fields, including environmental monitoring, astronomy, agricultural sciences, biological imaging, medical diagnostics, and food quality control\(^1\text{−}^6\). Driven by the enormous demands, various multispectral imaging techniques have been proposed, using color filter wheels, push-broom scanning, algorithms-aided coded apertures, and pixel-level filter arrays\(^5,^7\text{−}^9\). The spectral resolution has been readily improved to ~ 0.31 nm\(^10\) or 2.6 ~ 3.7 cm\(^{−1}\)\(^11\) requiring sophisticated optics and algorithms. Broadband photodetectors (PDs) with the ability to sense a broad spectral range and realize multispectral images could vastly simplify the systems and provide rich information, such as visible to MWIR fused images combining the appearance of visible light, texture composition of SWIR, and thermal detection of MWIR. However, the detectable spectral ranges of photodetectors are still in discrete bands, like ultraviolet-VIS, NIR, SWIR, and MWIR, limited by using bulk semiconductors like silicon (0.4 ~ 0.9 µm)\(^12,^13\), InGaAs (0.9 ~ 1.7 µm)\(^14,^15\), InSb or HgCdTe (3 ~ 5 µm)\(^16,^17\).

Various emerging low-dimensional materials have been proposed to achieve broadband photodetection\(^18\text{−}^21\). Two-dimensional (2D) material-based infrared photodetectors have attracted considerable research interests benefiting from their high responsivity, fast response, and tunable photodetection sensitivity\(^22\). Graphene has been demonstrated to be a promising material due to its gapless band structure that enables broadband absorption from the visible to infrared regime with 0.6 A W\(^{−1}\) at 0.8 µm and 11.5 A W\(^{−1}\) at 20 µm and operation speeds exceeding 50 GHz\(^23\). Besides graphene, other two-dimensional materials like black phosphorus (BP), transition metal dichalcogenide-based 2D materials (such as MoTe\(_2\), Bi\(_2\)Se\(_3\), and Bi\(_2\)Te\(_3\)), MXenes, and telluride have all been extensively investigated. With layer-dependent bandgap from 0.3 ~ 1.5 eV, BP-based photodetectors respond in the spectral range from 400 to 900 nm\(^24\). By introducing defect energy levels into layered MoS\(_2\),
photodetection for wavelengths from 445 nm to 9.5 µm has been demonstrated with an electronic state
density-dependent peak photoresponsivity of 21.8 mA W⁻¹ in the MWIR region²⁵. PdSe₂²⁶ and PtSe₂²⁷-
based photodetectors were reported to be responsive to long-wave infrared (LWIR) up to around 8 ~ 10
µm. Moreover, with 2D heterostructures, diverse optical functionalities can be realized with 2D/0D or
2D/2D configuration²,²⁰,²⁸. For example, by using MoS₂/BP heterostructures, polarization-sensitive
photoresponse was reported with room-temperature external quantum efficiencies (EQE) of 35% and
specific detectivity (D*) as high as 1.1 × 10¹⁰ Jones in the MWIR region²⁸. However, to realize broadband
multispectral imaging, array-format imagers are essential components. Despite the high sensitivity and
wide spectral detection ranges are obtained, 2D materials-based focal plane array (FPA) imagers have
rarely been reported.

Unlike chemical vapor deposited or epitaxially grown 2D materials, colloidal quantum dots (CQDs) can be
maturely monolithically integrated with silicon ROICs and CQDs-based FPA imagers have been
extensively studied²⁹–³⁴. Besides, CQDs have size-tunable band gaps and their detection ranges have
been extended from visible to long-wave infrared during the past decades³⁵–³⁸.

In 2009, Tobias Rauch et al. first integrated PbS CQDs on top of commercially available amorphous
silicon active matrix thin-film transistor panels with 256 × 256 pixels and 154 µm pixel pitch, achieving
NIR detection and imaging³⁹. Then, Jing Liu et al. improved the resolution of the PbS CQDs-based FPA
imagers with 640 × 512 pixels, enabling a high EQE of over 60% at 940 nm³³. Furthermore, the spectral
range of the PbS CQDs-based image sensor was extended to SWIR with a higher resolution of 768 × 512
pixels (cut-off wavelength of 1.45 µm, Interuniversity Microelectronics Centre (IMEC)) and 1920 × 1080
pixels (cut-off wavelength of 1.7 µm, SWIR Vision Systems). Recently, HgTe CQDs have gained extensive
attention for further extending the spectral range and have been successfully monolithically integrated
with silicon ROICs. In 2022, Charlie Gréboval et al. fabricated photoconductive HgTe CQDs-based 640 ×
512 FPA imagers with a 15 µm pixel pitch presenting an EQE of 4 ~ 5% for a cut-off wavelength around
1.8 µm³⁰. Then, a new device architecture of trapping-mode HgTe CQDs-based detectors was proposed
and demonstrated excellent 320 × 256 FPA imager performance with EQE up to 175%, and detectivity as
high as 2 × 10¹¹ Jones for extended SWIR with a cut-off wavelength of 2.5 µm at 300 K and 8 × 10¹⁰
Jones for MWIR with a cut-off wavelength of 5.5 µm at 80 K³². Furthermore, lateral p-n junctions were
constructed in the HgTe CQDs-based FPA imagers through a controllable in-situ electric field-activated
doping method enabling high-resolution SWIR imaging and improved performance compared with
photoconductor images before activation²⁹. However, due to their discrete energy levels induced by the
quantum confinement effect, the response of CQDs photodetectors usually presents peak-valley-like
features, and broadband detection over a wide spectral range is still missing.

To address those challenges, we propose a stacked PbS/HgTe CQDs photodetector configuration with
graded energy gaps, which leads to high carrier collection efficiency and ultrabroadband spectral
response from visible to MWIR (0.4 ~ 5 µm). More importantly, the high resolution 640 × 512 FPA imager
realizing ultrabroadband photodetection has been first fabricated as far as we know and the results show
low photoresponse non-uniformity (PRNU) down to 6%. With a noise equivalent temperature difference (NETD) of 34 mK, the ultrabroadband imager demonstrates high-resolution thermal images. With a set of optical filters, red, green, blue, SWIR, MWIR, and multispectral merged images have been successfully captured (Fig. 1).

**Visible to Mid-wave Infrared Ultrabroadband Photodetectors**

Figure 2a shows the fabricated ultrabroadband FPA imager. The sensing area consists of 640×512 pixels, and each pixel is made of three layers of VIS PbS CQDs, SWIR HgTe CQDs, and MWIR HgTe CQDs covering from 0.4 to 5 µm spectral region. The absorption spectra of PbS and HgTe CQDs from visible to MWIR are shown in Fig. 2b. The broadband PbS/HgTe CQDs FPA imager operates in a photoconductive mode with a pair of electrodes in each pixel.

The fabrication starts from the deposition of the MWIR HgTe CQDs layers by spin-coating. The spectral photoresponse of the photodetectors before and after the addition of SWIR HgTe CQDs layers was measured. The results show an enhanced SWIR response peak with an enhancement ratio of 5.31 at 2 µm, as shown in Fig. 2c. We then added PbS CQDs layers and compared the photoresponse of the SWIR/MWIR HgTe CQDs photodetectors before and after the addition of the PbS CQDs layers. The photoresponse in the visible and NIR region increases by a factor of 21.78 at 600 nm and 32.21 at 930 nm due to the contribution of PbS CQDs, as presented in Fig. 2d. Compared with the photoresponse of reference MWIR HgTe CQDs photodetectors, the broadband PbS/HgTe CQDs photodetectors demonstrate much-improved photoresponse under SWIR and visible light sources, as shown in Figure S1 in the supporting information. As a result, the photodetectors consisting of VIS PbS CQDs, SWIR HgTe CQDs, and MWIR HgTe CQDs layers exhibit ultrabroadband spectra from visible to MWIR (0.4 ~ 5 µm).

Interestingly, not only the response within the visible region of SWIR HgTe CQDs-based photodetectors after the addition of the VIS PbS CQDs layers is increased (Figure S2), but the SWIR response is also improved by two-fold at 2.16 µm, as presented in Fig. 2e. However, the SWIR HgTe CQDs layers hardly affect the MWIR response of MWIR HgTe CQDs-based photodetectors, as shown in Fig. 2c. We speculate the phenomenon could be attributed to the difference in interfacial built-in potential due to the graded energy gaps (Figure S3). The large energy band difference between the visible PbS CQDs layers and the SWIR HgTe CQDs layers perhaps facilitates the separation and collection of photo-excited carriers, achieving improved SWIR response.

The performance of ultrabroadband PbS/HgTe CQDs photodetectors is characterized using a calibrated high-temperature blackbody as light sources. The temperature of the blackbody is set as 1500°C, realizing the full spectrum coverage from visible to MWIR, as shown in Figure S4. The photodetector performance was measured in a thermostat under the vacuum with different working temperatures between 80 K and 300 K. The schematic diagram of the performance measurement process is presented in Fig. 3a. Figure 3b shows the measured current density versus voltage curves of ultrabroadband PbS/HgTe CQDs photodetectors at 300 K and 80 K. The darkcurrent density significantly decreases from
28.54 µA mm⁻² at 300 K to 0.09 µA mm⁻² at 80 K under the voltage of 1 V. With lowered temperature, the detectivity of ultrabroadband PbS/HgTe CQDs photodetectors can be improved from 3.9 × 10⁹ Jones at 300 K to 6.5 × 10¹⁰ Jones at 80 K, as shown in Fig. 3c. There is an order of magnitude higher detectivity of ultrabroadband photodetectors at 300 K compared with the reference MWIR HgTe CQDs photodetectors (Fig. 3c). Details of the performance calculation process can be found in the supporting information section 2. Therefore, the proposed stacked PbS/HgTe CQDs photodetectors can not only stitch the spectral response from the three CQDs with different energy gaps together but also demonstrate high sensitivity and detection performance.

**Ultrabroadband Focal Plane Arrays Imagers**

The proposed ultrabroadband photodetector configuration is fully compatible with the CMOS fabrication process, and we extend the ultrabroadband photodetectors from a single-element device to an array-format FPA imager. Ultrabroadband VGA format FPA imagers with 640 × 512 pixels and a pixel pitch of 15 µm were fabricated and characterized at 80 K. The detailed pixel design and performance calculation process of FPA imagers are shown in section 3 of the supporting information.

Figure 4a shows the distribution histogram of darkcurrent density of each pixel in the FPA imager and the darkcurrent mapping of the FPA imager. The darkcurrent densities of ultrabroadband FPA imagers are low and mainly around 2 × 10⁻⁵ A cm⁻². Besides, the ultrabroadband FPA imagers exhibit a high responsivity of 2.88 ± 0.06 A W⁻¹, as shown in the responsivity distribution histogram of Fig. 4b. The photoresponse mapping of the ultrabroadband FPA imagers is shown in the inset of Fig. 4b. Then, the photoresponse non-uniformity (PRNU) is calculated by

\[
PRNU = \frac{1}{V_{signal}} \sqrt{\frac{1}{M \times N - (d + h)} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ V_{signal}(i, j) - \bar{V}_{signal} \right]^2} \times 100\%
\]

where \(M\) is the total number of pixels in a row, \(N\) is the total number of pixels in a column, \(d\) is the number of dead pixels, \(h\) is the number of over heat pixels, \(V_{signal}(i, j)\) is the signal voltage of \(i^{th}\) row and \(j^{th}\) column, and \(\bar{V}_{signal}\) is the average responsivity for FPA imager. The dead pixel is defined as the pixel with a signal lower than 50% of the average signal. The over heat pixel is the pixel with noise two times higher than the average noise. The calculated PRNU of ultrabroadband FPA imagers is as low as 6%.

The detectivity is also a critical figure of merit of FPA imagers reflecting the signal-noise ratio. The ultrabroadband FPA imagers demonstrate a high detectivity of an average value of about 3.15 × 10¹⁰ Jones, as shown in Fig. 4c. Besides PRNU, the non-effective pixel rate is another important performance index for array-format FPA imagers. Non-effective pixels can be categorized into two groups: dead pixels and over heat pixels. The non-effective pixel mapping with three dead pixels and five over heat pixels is shown in Fig. 4d. The operability of ultrabroadband FPA imagers is as high as 99.99%.
With an MWIR optical filter, we further characterized the performance of ultrabroadband FPA imagers for thermal imaging. One key indicator for thermal imaging is noise equivalent temperature difference (NETD), which is calculated by

$$\text{NETD} = \frac{1}{M \times N - (d + h)} \sum_{i=1}^{M} \sum_{j=1}^{N} \left( \frac{T - T_0}{V_s(i, j)/V_N(i, j)} \right)$$

where $M$ is the total number of pixels in a row, $N$ is the total number of pixels in a column, $d$ is the number of dead pixels, $h$ is the number of over heat pixels, $T$ is the high blackbody temperature, $T_0$ is the low blackbody temperature, $V_s(i, j)$ is the signal voltage difference under the different blackbody temperature, and $V_N(i, j)$ is the noise voltage under low blackbody temperature. By tuning the integration time, the NETD of ultrabroadband FPA imagers is varied, as shown in Fig. 4e. The NETD is down to 34 mK with an integration time of 10 ms. The corresponding NETD mapping is presented in Figure S7. Over 50 ultrabroadband FPA imagers have been fabricated and the average NETD is consistent with a derivation of 34.72 ± 10.88 mK, as shown in the inset of Fig. 4e. Attributed to excellent NETD performance, the high-quality thermal images captured by the ultrabroadband FPA imager with an MWIR optical filter are obtained, as shown in Fig. 4f. The details of human hair (i) and human hand veins (ii) are very clear from the thermal images. Besides, the imaging results distinctly show the difference between inhaling (iii) and exhaling (iv) while a human wearing the mask.

The stacked VIS PbS/ SWIR HgTe/ MWIR HgTe CQDs layers with the dual-graded energy gaps enable the efficient merging of three spectral response channels with high sensitivity. In addition, benefiting from the solution processability of CQD materials, the PbS/HgTe CQDs photodetectors could be monolithically integrated with silicon ROICs, achieving high-resolution 640 × 512 FPA imagers. Although the 2D material-based photodetectors possess a wide spectral response range from visible to LWIR, those are difficult to extend to FPA imagers (Table 1). Besides, despite the high-resolution CQDs-based FPA imagers have been widely studied, broadband detection over a wide spectral range is still missing (Table 1). Compared with prior reports, the ultrabroadband PbS/HgTe CQDs FPA imagers in this work for the first time combine high imaging resolution with 640 × 512 pixels, wide spectral response range from visible to MWIR, and excellent NETD of 34 mK (Table 1).

### Multispectral and Ultrabroadband Imaging

We further demonstrate the multispectral imaging capability of the ultrabroadband FPA imagers and the multispectral imaging setup is illustrated in Fig. 5a. With a set of optical filters, such as red, green, blue, SWIR, and MWIR filters, single-band images can be obtained, and a multispectral image is reconstructed by merging each spectral channel. The apple with the “BIT” scratch wrapped in the glove, peach, and pear are chosen as the image objects containing red, green, and blue colors and different material compositions. Using red, green, and blue filters, red, green, and blue single-color images are achieved, and a reconstructed full-color visible image is shown in Fig. 5a. The “BIT” scratch on the surface of the apple wrapped in the glove can be distinctly observed that is captured by ultrabroadband imagers with SWIR
filters (Fig. 5a). The reconstructed multispectral visible and SWIR merged images could both display full visible colors and detect food qualify (Fig. 5a).

Ultrabroadband imaging can offer richer and more valuable optical information employing just one imager. The ultrabroadband FPA imagers output images adaptively, according to the intensity distribution of the incident light. As a visual demonstration of device performance, images are captured by the ultrabroadband FPA imagers under different lighting conditions. Without an external light source like a tungsten lamp or sunlight, the MWIR response from the thermal emission of objects dominates in the captured images. A set of room-temperature solvents (from left to right: DDT, TCE, IPA, alcohol, deionized water, and acetone) can not be distinguished that is captured by ultrabroadband imagers under dark conditions (Fig. 5b (ii)). However, with tungsten lamp illumination, the different solvents show distinct greyscale due to the enhanced SWIR response (Fig. 5b (iii)). Besides, the opaque silicon wafer blocking the bottles in visible light (Fig. 5b (i)) becomes transparent when it is captured by ultrabroadband imagers (Figs. 5b (ii) and (iii)). In addition, thermal distribution images of a cup of hot water (80°C), a cup of liquid nitrogen (-200°C), and a human hand can be clearly displayed which is captured by ultrabroadband imagers under dark conditions (Fig. 5c (ii)). With tungsten lamp illumination, merged responses from visible, SWIR, and MWIR can be recorded simultaneously. The printed logo, the different greyscale room-temperature solvents (from left to right: DDT, TCE, IPA, and deionized water), the cups of hot water and liquid nitrogen, the silicon wafer, the human hand with wearing bracelet can be all distinctly seen containing broadband information from visible to MWIR that is captured by ultrabroadband imagers (Fig. 5c (iii)).

Compared to single-band images, ultrabroadband images offer more information about thermal distribution, textures, materials, and details of geometry. The human under sunlight images captured with ultrabroadband FPA imager could clearly display the human body shape, human hair, sunglasses, clothing appearance, plastic buttons of clothes, sweat stains inside of clothes, shadow, and surrounding environment such as trees and railing, demonstrating high-resolution from visible to MWIR ultrabroadband merged imaging ability (Fig. 5d). A video captured by the ultrabroadband FPA imagers under different light conditions can be found in the supporting information movie.

**Conclusion**

In conclusion, we develop a stacked PbS/HgTe CQDs photodetector configuration with gradient energy gaps, which leads to ultrabroadband spectral response from visible to MWIR and an order of magnitude higher detectivity compared with reference MWIR HgTe CQDs photodetectors. More importantly, the ultrabroadband PbS/HgTe CQDs photodetectors have been successfully extended to array-format FPA imagers with 640 × 512 pixels and a pixel pitch of 15 µm. The ultrabroadband FPA imagers exhibit excellent performance with a low PRNU of 6%, high detectivity of $3.15 \times 10^{10}$ Jones, low NETD of 34 mK, and high-resolution thermal images under dark conditions. Furthermore, the ultrabroadband FPA imagers demonstrate the ability of multispectral imaging obtaining red, green, blue, SWIR, and MWIR images by
using a set of optical filters, and ultrabroadband imaging merging visible to MWIR different band features.

**Methods**

**Synthesis of colloidal materials.**

**HgTe CQDs**

The synthesis of HgTe CQDs is similar to previous reports\(^\text{29,42}\). HgCl\(_2\) (Strem Chemicals, 99%, 0.4 mmol) was dissolved in 16 ml of oleylamine (Aladdin) in a 30 ml glass vial at 100°C for 1 hour with stirring in the glove box. The temperature was then adjusted to the reaction temperature and stabilized for 30 min. Tellurium power (SIGMA-ALDRICH, 99.999%) in trioctylphosphine (TOP, SIGMA-ALDRICH, 97%) solution (1 M, 0.4 ml) was rapidly injected. The clear solution immediately turned black. The reaction temperature and reaction time depend on the target size for the HgTe CQDs. In our experiments, 75 ~ 80°C for 4 min and 95 ~ 100°C for 10 min are typical conditions for SWIR and MWIR HgTe CQDs. The reaction was quenched by injecting a solution of 3 ml dodecanethiol (DDT, SIGMA-ALDRICH, 98%) and 0.4 ml TOP in 16 ml tetrachloroethylene (TCE, Aladdin, 98%). After quenching, the vial was quickly removed from the glove box and cooled down. The solution was precipitated with an equal volume of isopropanol (IPA) and centrifuged at 5000 r.p.m. for 5 min. Finally, the precipitate was resuspended in 16 ml of chlorobenzene (CBZ, Aladdin, 99.5%) and stored under ambient conditions.

**PbS CQDs**

The synthesis of PbS CQDs is similar to the previous report\(^\text{43}\). In a three-neck reaction flask, 0.45 g (2 mmol) of PbO, 18 mL of octadecene (ODE), and 1.5 mL of oleic acid (OA) were pumped at 120 °C under vacuum for ~16 h. A sulfur precursor solution was prepared by mixing 0.18 mL of bis-(trimethylsilyl)sulfide with 10 mL of ODE in the glove box. The sulfur solution was quickly injected into the reaction flask at 120 °C, and then the solution was allowed to slowly cool down to room temperature. The PbS CQDs were isolated by the addition of 60 mL of acetone followed by centrifugation. The CQDs were then purified by dispersion in toluene and reprecipitation with acetone and redissolved in anhydrous toluene. The solution was washed with methanol three times with the final redispersion in octane.

**Device fabrication.**

Ultrabroadband photodetectors were fabricated on the interdigitated electrodes. Before spin-coating the CQD solutions, the substrate was treated with 3-mercaptopropyltrimethoxysilane (MPTS) for 30 s and rinsed with IPA. The MWIR HgTe CQDs solution was spin-coated on the substrate to build up films with a thickness of about 400 nm. Then the SWIR HgTe CQDs solution was spin-coated on the MWIR HgTe CQDs layers to build up films with a thickness of about 400 nm. Finally, the PbS CQDs solution was spin-coated on the SWIR HgTe CQDs layers to build up films with a thickness of about 400 nm. Each HgTe CQD layer was treated with 1,2-ethanedithiol (EDT)/HCl/IPA (1:1:50 by volume) solution for 10 s, rinsed
with IPA, and dried. Each PbS CQD layer was treated with tetrabutylammonium iodide (TBAi) in methanol solution for 30 s, rinsed with IPA, and dried. All the treatments are conducted in ambient conditions at room temperature.

**Device characterization.**

The calibrated high-temperature blackbody was used as the light source. The photodetector was placed in a thermostat for performance characterization. Current density versus voltage curves were measured using the source meter (Keithley 2602B). The imaging of CQD imagers was conducted with a focal plane array tester, which can provide power, ground, timing, and trigger signals. The output channels from the ROICs were sampled and reordered to construct raw images. The performance, at both the array and pixel levels, can be assessed.

**Declarations**

**Acknowledgements**

This work was supported by National Key R&D Program of China (2021YFA0717600), National Natural Science Foundation of China (NSFC No. 62035004, NSFC No. U22A2081, and NSFC No. 62305022). X.T. is sponsored by the Young Elite Scientists Sponsorship Program by CAST (No. YESS20200163). P.Z. is supported by the BIT Research and Innovation Promoting Project (Grant No. 2022YCXZ021).

**Author contributions**

All authors contributed to the manuscript.

**Competing interests**

The authors declare no competing interests.

**Data availability**

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

**References**


**Table 1**
Table 1
Comparison of device performance of single-element photodetectors or FPA imagers with 2D materials and CQDs.

<table>
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<th>System</th>
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<th>Resolution</th>
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<th>NETD (mK)</th>
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Figures
Figure 1

Schematic diagram of ultrabroadband visible to MWIR sensing and imaging.
**Figure 2**

Ultrabroadband PbS/HgTe CQDs imagers.  

a. Picture and schematic diagram of an ultrabroadband PFA imager with stacked PbS/HgTe CQDs layers.  
b. Absorption spectra of PbS and HgTe CQDs from visible to MWIR region.  
c. Spectral response of MWIR HgTe CQDs-based photodetectors without and with SWIR HgTe CQDs layers.  
d. Spectral response of broadband photodetectors with stacked VIS PbS, SWIR, and MWIR HgTe CQDs layers and reference photodetectors without VIS PbS layers.  
e. Spectral response of SWIR HgTe CQDs-based photodetectors without and with VIS PbS CQDs layers.

**Figure 3**

- Voltage (V) vs. Current density (µA mm⁻²) graph with curves for Dark current and Photocurrent at different temperatures.
- Temperature (K) vs. Detectivity (Jones) graph with comparisons between MWIR HgTe Ref, Broadband PDs, and SWIR HgTe CQDs-based photodetectors.
Ultrabroadband PbS/HgTe CQDs photodetectors performance. a. Schematic diagram of the performance measurement process. b. Current density versus voltage curves of ultrabroadband PbS/HgTe CQDs photodetectors with and without illumination. The light source is a calibrated blackbody at a temperature of 1500°C. c. Detectivity versus temperature curves of ultrabroadband PbS/HgTe CQDs photodetectors and reference MWIR HgTe CQDs photodetectors.

Figure 4

Ultrabroadband PbS/HgTe CQDs FPA imagers performance. a. Distribution histogram of darkcurrent density of each pixel in the FPA imager. The inset shows the darkcurrent mapping of the FPA imager. b. Distribution histogram of the response of each pixel in the FPA imager. The inset shows the response mapping of the FPA imager. c. Distribution histogram of detectivity of each pixel in the FPA imager. The inset shows the detectivity mapping of the FPA imager. d. Non-effective pixel mapping of the FPA imager. e. The NETD versus integration time curves of FPA imager at 80 K. The inset shows the distribution histogram of NETD of each pixel in the FPA imager. f. Thermal images captured by the ultrabroadband FPA imager with an MWIR optical filter.
Figure 5

Multispectral and ultrabroadband imaging. **a.** Illustration of the multispectral imaging setup using the ultrabroadband FPA imagers. Red, green, and blue images and the reconstructed full-color visible image. SWIR image and the reconstructed visible and SWIR merged image. **b.** Images of a group of chemical solvents behind a silicon wafer captured with a CMOS camera (i), ultrabroadband FPA imager without (ii), and with a tungsten lamp (iii). **c.** Images of bottles of different chemical solvents, cups of hot water and liquid nitrogen, a background board with different logos, and a human hand wearing a bracelet holding the silicon wafer captured with a CMOS camera (i), ultrabroadband FPA imager without (ii) and with a tungsten lamp (iii). **d.** Visible to MWIR merged image captured with ultrabroadband FPA imager.

**Supplementary Files**

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