Melt-Growth Large-Sized Cs₂TeI₆ Crystals for X-Ray Detection with Low Detection Limit

Large-Sized Defect Perovskite Cs₂TeI₆ Grown from a Melt for X-Ray Detection

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Abstract:

Recently, lead halide perovskites, as a new generation of direct X-ray detector, demonstrate outstanding detection performance for X-ray radiation. However, the toxicity of Pb and environmental instability hinder their application. Here, we report a lead-free perovskite Cs₂TeI₆ bulk crystal for X-ray detector. Cs₂TeI₆ polycrystal was first synthesized by directionally reaction of CsI, Te and I₂ and large Cs₂TeI₆ single crystal with the dimension of $\Phi 10\text{ mm} \times 55\text{ mm}$ was grown by the vertical Bridgman method. The as-grown Cs₂TeI₆ single crystal has the bandgap of $\sim 1.47\text{ eV}$, resistivity of $9.92 \times 10^{11}\ \Omega \cdot \text{cm}$ at room temperature. Au/Cs₂TeI₆/Au device made from our Cs₂TeI₆ crystal shows the X-ray sensitivity of $27.8\ \mu\text{C} \cdot \text{Gy}^{-1} \cdot \text{cm}^{-2}$ with the detection limit as low as $72.5\text{ nGy} \cdot \text{s}^{-1}$. The above results demonstrate that Cs₂TeI₆ single crystal possesses the potential application of medical imaging and security screening.

Keywords:

Cs₂TeI₆ perovskite; vertical Bridgman; carrier transport behavior; X-ray detection.

1. Introduction

X-ray detection is an important technology for wide applications, such as industrial non-destructive inspection, medical diagnostics and scientific research, etc [1-3]. Solid-state semiconductor detectors, which can directly convert X-ray photons to electrical signal, enable a higher spatial resolution and a simple system configuration [4]. With the rapid advances in fabrication technology, various materials, such as α -Se [5], PbI_2 [6], HgI_2 [7], CdZnTe [8], etc. have been explored for X-ray detection.

Lead halide perovskites with a general formula of APbX_3 [$\text{A}=\text{CH}_3\text{NH}_3^+$ (MA^+), $\text{NH}_2\text{CHNH}_2^+$ (FA^+), Cs^+ , $\text{X}=\text{Cl}^-$, Br^- , I^-], have been used as excellent optoelectronic materials for solar cells [9, 10], light-emitting diodes [11], photodetectors [12], lasers [13], *etc.* However, many characteristics of these materials, including large average atomic number, suitable bandgap, high resistivity, and large charge carrier mobility-lifetime product, suggest them to be promising candidates for X-ray detection. Sensitive X-ray detectors based on MAPbI_3 thin films [14], MAPbBr_3 [15, 16], CsPbBr_3 [17], *etc.* have been reported to possess impressive X-ray detection sensitivity. However, the most current halide perovskites contain toxic element Pb. The wide range of disorders, such as memory problems and intellectual disability [18] and the high solubility in water also hinders the application of these lead-based halide perovskites. Hence, it is important to explore lead-free, moisture-stable and better detection limits halide perovskites for X-ray detection.

Lead-free perovskite Cs_2TeI_6 adopts K_2PtCl_6 structure type with good air and moisture stability [19]. Unlike the traditional ABX_3 perovskite structure, Cs_2TeI_6 could

be viewed as a variant-constructed 0-D perovskite on the basis of isolated $[\text{TeI}_6]^{2-}$ octahedra, which can also be written as $\text{CsTe}_{0.5}\text{I}_3$ due to the deficiency of half-octahedra Te in the crystal [20, 21]. In addition, Cs^+ cations, which form a regular 12-fold coordination with I^- anions, fill in the sites between $[\text{TeI}_6]^{2-}$ octahedra. Compared with traditional ABX_3 perovskite, the structure of Cs_2TeI_6 is more stable, which could avoid the structural phase transitions induced by the mismatch in ionic radii of the constituent atoms [22, 23]. The higher structural and environmental stability is beneficial for Cs_2TeI_6 perovskite to be applied in X-ray detection. A high sensitive X-ray detectors based on Cs_2TeI_6 thick film was realized with the value of $192 \text{ nC}\cdot\text{R}^{-1}\cdot\text{cm}^{-2}$ under 40 kVp X-rays at an electrical field of $250 \text{ V}\cdot\text{cm}^{-1}$ [24]. However, the poor film quality, the high density defects and the incomplete attenuation of X-ray of Cs_2TeI_6 thick films limit its X-ray detection performance. Cs_2TeI_6 single crystal with low trap density and high charge collection efficiency would show better X-ray detection performances. Cs_2TeI_6 films and polycrystals can be grown using low temperature solution method, it is still a challenge to grow large-sized crystals due to the difficulty to choose suitable solvents, growth temperatures, *etc* [25]. Melt method seems possible to obtain large Cs_2TeI_6 single crystals. However, the decomposition of TeI_4 brings difficult to synthesize Cs_2TeI_6 polycrystals.

In this work, we investigate the polycrystal synthesis and the melt growth of Cs_2TeI_6 single crystals by the vertical Bridgman method. The optical properties of the as-grown Cs_2TeI_6 crystal are characterized and X-ray responses of the self-fabricated $\text{Au}/\text{Cs}_2\text{TeI}_6/\text{Au}$ devices are measured. Furthermore, the carrier mobilities are

evaluated by time-of-flight technology under radiation of ^{241}Am α particles at room temperature.

2. Materials and methods

2.1 Synthesis of Cs_2TeI_6 polycrystals

Polycrystalline Cs_2TeI_6 was synthesized using high purity CsI (5N, powder) Te (7N, lumps) and I_2 (4.5N, granules). A total mass of 15 g raw materials were weighed in the stoichiometric ratio of $\text{CsI}:\text{Te}:\text{I}_2=2:1:2$ with 5% excess of iodine, which prevents iodine element vaporization due to its high vapor pressure. The raw materials were loaded into a quartz ampoule (Outer diameter: 19 mm; Inner diameter: 15 mm) and sealed under 5×10^{-5} Pa. Several synthesis processes were performed to obtain the pure Cs_2TeI_6 polycrystals. First, the sealed ampoule was heated from room temperature to 150 °C (lower than the boiling point of iodine which is ~180 °C) and maintained for 10 h in a resistant furnace. After that, the ampoule was soaked at 200 °C. Then, the temperature was gradually risen to 550 °C in 24 h and kept for 24 h for the synthesis, and finally cooled down to room temperature. The second process was done as follows, the sealed ampoule was also heated to 550 °C in a rocking furnace by the same heating process with the first. Subsequently, the furnace was rocked up and down slowly for 12 h at 550 °C for fully mixture of the materials. Then, the ampoule was cooled down to 400 °C and kept at 400 °C for 24 h for homogenization before cooling down to room temperature.

2.2 Crystal growth

Cs_2TeI_6 crystals were grown by the vertical Bridgman method. The synthesized

Cs₂TeI₆ polycrystals were loaded into a carbon-coated quartz ampoule with an inner diameter of 10 mm and sealed under 5×10^{-5} Pa. Then, the sealed crucible was put in a two-zone Bridgman furnace with a temperature gradient of ~ 10 K/cm. Several attempts of the crystal growth were performed using different overheating temperature and holding time prior to the ampoule descend along the axis of the furnace. The overheating temperature and time were set at 650 °C for 24 h and 610 °C for 12 h prior to crystal growth, respectively. The withdraw rate of the crucible was 0.5 mm/h. After the growth, the crucible was cooled down to room temperature at a rate of 5 K/h.

A black Cs₂TeI₆ ingot with the dimension of $\Phi 10$ mm $\times$ 55 mm was grown from the melt. Wafers with dimension of $5 \times 5 \times 2$ mm³ were sliced from the as-grown ingot, which are mechanically polished by abrasive paper and polishing cloth to obtain a flat and smooth surface prior to the measurements.

2.3 Device fabrication

To fabricate a planar detector, Au electrodes with the thickness of ~ 70 nm were thermally evaporated onto two opposite sides of the $5 \times 5 \times 2$ mm³ wafers. Then one of the electrodes was bonded by carbon paste to a sample holder, and the opposite one was connected using a Cu wire.

2.4 Characterizations

The powder X-ray diffraction (XRD) of as-grown Cs₂TeI₆ crystal was collected on a RICOH D/Max-2500 using Cu-K α radiation as an X-ray source, scanned from 10° to 80° with a step width of 0.02°. A Rietveld refinement of the structure was

performed on the diffraction data using the General Structure Analysis Software package (GSAS-EXPGUI) [26, 27]. Element compositions and morphologies of Cs₂TeI₆ crystals were carried out using a JSM-7500F Field Emission Scanning Electron Microscope (FESEM) with an Oxford Instruments model X-Max50 Energy Dispersive X-Ray spectroscopy (EDS). The UV-Vis-NIR transmittance data was recorded over the spectral range of 500-2000 nm at room temperature using a Shimadzu UV-3150 spectrometer. Current-voltage (I-V) and current-time (I-t) curves were measured by Keithley 6517B and the light emitting diode (LED) was employed as the illumination source to perform time-dependent photoresponse with a wavelength of 425 nm.

2.5 Detector performance measurements

A tungsten-target X-ray tube (SPELLMAN XRB011) was used as X-ray source, which was constantly operated with a tube voltage of 40 kV, and the tube current from 5 to 60 μ A. The X-ray dose rate was calibrated using a thermoluminescence meter (as shown in Fig. S1, Supporting Information). The device was placed in a dark shielding box to prevent disturbance from ambient light. The bias voltage was applied to the device and the induced photocurrent was recorded by a Keithley 6517B instrument.

The pulse height spectra as a function of bias voltage were obtained from a sample irradiated by an uncollimated ²⁴¹Am @ 5.49 MeV α particle source. The pulse shape information was simultaneously recorded by the preamplifier output of a high-speed waveform digitizer card. The signals from the preamplifier (ORTEC 570) were further amplified and shaped by the amplifier (ORTEC 142) with a gain of 5-200

and shaping time of 2 μ s. The final signals were subsequently evaluated by a dual 8 K input multichannel analyzer (Imdetek AMCA-01) and read into software, which generated and displayed the response spectrum.

3. Results and discussion

Prior to crystal growth, several synthesis processes were performed and pure Cs_2TeI_6 polycrystals were obtained, as shown in Fig. 1(a). The synthesized Cs_2TeI_6 polycrystals were ground in an agate mortar to determine the phase structure and the purity by powder X-ray diffraction measurements. As shown in the top of Fig. 1(b), the peaks of CsI could be observed in the sample by first synthesis process (1st), ascribed to incomplete reaction of the raw materials and the loss of iodine by the volatilization. This can also be confirmed by the purple iodine deposited on the ampoule top, as shown in the inset of Fig. 1(b). Compared to the first synthesis process, by using the second synthesis process, i.e. mixing at 550 °C followed by homogenization at 400 °C, CsI phase was eliminated. No purple iodine in the ampoule was seen and no CsI peaks observed in the 2nd XRD spectra. Pure Cs_2TeI_6 polycrystals are obtained.

Fig. 1. (a) Heating and cooling process of the first (1st) and second (2nd) synthesis methods for Cs_2TeI_6 polycrystals. (b) The corresponding powder XRD data of the synthesized polycrystals. The inset are the pictures of the ampoule with and without purple iodine.

The self-synthesized pure Cs_2TeI_6 polycrystals were used for the crystal growth by Bridgman method as described before. Initially, overheating temperature was set at 650 °C and kept for 24 h, which resulted in the ampoule bursting because of the overpressure from iodine. Then, the overheating temperature was reduced to 610 °C for 12 h, a black Cs_2TeI_6 ingot with the dimension of $\Phi 10 \text{ mm} \times 55 \text{ mm}$ was successfully obtained, as shown in Fig. 2(b). The matte surface of the ingot was attributed to the adhesion with the carbon-coated quartz ampoule. Small particles from the middle part of the ingot were characterized by SEM and EDS to determine the chemical composition and the composition uniformity of the as-grown Cs_2TeI_6 crystal, and the results are shown in Fig. 2(c). The element mappings show that Cs, Te and I are homogeneously distributed in Cs_2TeI_6 crystal. Moreover, the chemical

composition of as-grown crystal is Cs:Te:I=2:1.12:6.02, which is close to the stoichiometric ratio. The structure and the phase purity of the as-grown Cs₂TeI₆ crystal were also measured by powder XRD measurements. All diffraction peaks shown in Fig. 2(d) index to the standard card of Cs₂TeI₆ (PDF#46-0162), which indicate the phase purity of the as-grown crystal. Additionally, the characteristic diffraction peak (2 2 2) shifts to lower diffractions angels from 26.53° to 26.24° due to the lattice deformation. Further, Rietveld refinement analysis was conducted using GSAS-EXPGUI program to determine the actual lattice constant ^[26, 27]. As shown in Fig. 2(d), the calculated patterns (solid red line) agree very well with the experimental one with the reliability parameters of R_{wp}=14.60% and R_p=10.37%. Based on the result, the refined lattice parameters are $a=11.7137(8)$ Å with the space group of *Fm-3m*, which is in agreement with the previous reports of cubic Cs₂TeI₆ ^[28, 29].

Fig. 2. (a) Structure of Cs_2TeI_6 crystal. (b) As-grown Cs_2TeI_6 ingot with the dimension of $\Phi 10 \text{ mm} \times 55 \text{ mm}$. (c) SEM image and the corresponding EDS mappings of the as-grown Cs_2TeI_6 crystal. (d) The Rietveld refinement of the powder XRD data of the as-grown Cs_2TeI_6 crystal by GSAS-EXPGUI. Circles are the experimental data and solid red line is the refinement result. The difference between the experimental and calculated results is shown by the blue line. The green tick marks indicate the expected Bragg peak positions for Cs_2TeI_6 phase.

To demonstrate the band gap of the as-grown Cs_2TeI_6 crystal, UV-Vis-NIR transmittance spectra ranged from 500 to 2000 nm were collected at room temperature,

as shown in Fig. 3(a). A sharp decrease was observed in the transmittance spectra of the sample from 900 nm to 800 nm, which was ascribed to the strong absorption. The energy gap value of Cs₂TeI₆ can be estimated according to Tauc law ^[30]:

$$[\alpha h\nu]^n = A(h\nu - E_g) \quad (1)$$

where $h\nu$ is the incident photon energy, α is the absorption coefficient, A is a proportional constant, E_g is the value of the band gap, n is a parameter dependent on the type of electronic transition responsible for the absorption. For an indirect band gap semiconductor of Cs₂TeI₆, the value of n is 1/2 ^[25]. By extrapolating the linear portion of the curves of $[\alpha h\nu]^{0.5}$ vs. $h\nu$ to zero, the resulting indirect band gap of Cs₂TeI₆ is ~1.47 eV, which is good agreement with previous reports ^[24, 31] and suitable for radiation detection materials.

To evaluate the optoelectronic properties, Au/Cs₂TeI₆/Au device was fabricated based on Cs₂TeI₆ crystal with the dimension of 5×5×1.74 mm³, as schematically shown in the inset in Fig. 3(b). The dark current of Cs₂TeI₆ crystal under voltage range from -50 V to 50 V was shown in Fig. 3(b). A quite low dark current of ~12 pA at 50 V was beneficial for obtaining high signal-to-noise ratio. The resistivity of Cs₂TeI₆ was calculated to be as high as 9.92×10¹¹ Ω·cm, which is 1~3 orders of magnitude higher than CdZnTe ^[32], CsPbBr₃ ^[17] and MAPbBr₃ ^[33], *etc.* The high resistivity of Cs₂TeI₆ was mainly ascribed to its special electronic structure and low vacancy due to the high formation energy of iodine vacancies, which reduced the shallow-level defects that can provide free charge carries ^[25].

The photocurrent of Cs₂TeI₆ device was measured to evaluate the photoelectrical

response. Fig. 3(c) shows the current-time photoresponse curves of Cs₂TeI₆ irradiated by blue light (425 nm) with various power density from 1.0 mW·cm⁻² to 28.8 mW·cm⁻² under the applied voltage of 100 V. Obviously, significant overshoot could be seen when the illumination was on due to the sudden excited and departed carriers [34]. The ratio of on-off current increased from 2.5 to 7.6 with increasing incident light power density (as shown in Fig. S2, Supporting Information). Furthermore, the photocurrent gradually increased with the incident light power density, attributed to more electron-hole pairs generated excited by more incident photons. The inset of Fig. 3(c) shows the power density-dependent photocurrent, the curve is well fitted by $I \propto P^{0.38}$. The index of 0.38 is not close to the ideal value 1, indicates that high density trap states existed in the energy gap [35].

Fig. 3. (a) The transmittance spectrum of Cs₂TeI₆ crystal at room temperature, the inset shows the band gap fitted by Tauc plot curve. (b) Linear current-voltage curve under voltage from -50 V to 50 V, the inset shows the photograph of the Au/Cs₂TeI₆/Au device. (c) Current-time (I-t) curves of Cs₂TeI₆ illuminated by blue light with a wavelength of 425 nm and power density of 1.0 mW·cm⁻² to 28.8 mW·cm⁻². The insert is the power-dependent photocurrent illuminated by blue light under 100 V.

To investigate the X-ray detection performance, Cs₂TeI₆ device was tested with the X-ray tube as radiation source at the voltage of 40 kV, while the radiation dose

rate was carefully adjusted by changing the current of the X-ray tube. To evaluate the X-ray detection sensitivity, the device was illuminated with the dose rate ranged from 72.5 nGy·s⁻¹ to 532.4 nGy·s⁻¹, as shown in Fig. 4(a). Obviously, the photocurrent was increased when the X-ray is on. Hence, the dose rate-dependent photocurrent densities were obtained as shown in Fig. 4(b). The X-ray sensitivity (S) of the detector was defined as the charge released per unit area per unit exposure of radiation, $S = \Delta I / (A \times D)$, where ΔI is the difference between the photocurrent and dark current, A is the electrode area, and D is the X-ray dose rate [5]. The sensitivity of 27.8 $\mu\text{C} \cdot \text{Gy}^{-1} \cdot \text{cm}^{-2}$ was obtained by linear fitting the current density vs. dose rate. Compared with the tradition materials $\alpha\text{-Se}$ (20 $\mu\text{C} \cdot \text{Gy}^{-1} \cdot \text{cm}^{-2}$), Cs_2TeI_6 detector possess a higher X-ray detection sensitivity under the relatively low electric field (2.76 V·mm⁻¹). The noise current was evaluated by calculating the standard deviation of the photocurrent (as detailed in Fig. S3, Supporting Information).

In order to evaluate the detection limit, the signal-to-noise (SNR) ratio was derived under varies dose rates, as shown in Fig. 4(c). The dose rate with SNR value of 3 as the detection limit at a given electric field was defined by International Union of Pure and Applied Chemistry (IUPAC) [36]. All the resulting SNRs in Cs_2TeI_6 detector are above 3. Furthermore, the detection limit is the most important figure of merit for evaluating the performance of an X-ray detector for medical imaging and security screening. Cs_2TeI_6 detector could respond to the X-ray even the dose rate lowered to 72.5 nGy·s⁻¹, much lower than the regular medical diagnostics (5.5 $\mu\text{Gy} \cdot \text{s}^{-1}$) [37, 38], which allows Cs_2TeI_6 detector to be a candidate for medical imaging and

security screening. The low detection limit of Cs₂TeI₆ detector was mainly attributed to the low noise current of 0.014 pA, but could also be ascribed to the charge collection efficiency (CCE) or gain, which could be calculated as:

$$\text{CCE} = \frac{Q}{Q_0} = \frac{I_R}{I_P} \quad (2)$$

where I_R is induced photocurrent and I_P is theoretical photocurrent induced by X-ray ionization, which is defined as $I_P = \varphi \beta e$, where e is the quantity of electric charge. The photon absorption rate φ can be defined as $\varphi = \varepsilon D m_s / E_{ph}$, where ε is the fraction of absorbed photons in the sample ($\varepsilon = 1$, as shown in Fig. S4, Supporting Information), D is the dose rate, m_s is the mass of the sample, E_{ph} is the photon energy. β is the maximum number of photo-generated carriers per photon, given by $\beta = E_{ph} / \Delta$, where Δ is calculated by the empirical model of $\Delta = 3E_g$ [39]. The CCE of Cs₂TeI₆ X-ray detector was ~50% for a dose rate of 532.4 nGy·s⁻¹, which is higher than those in Cs₂AgBiBr₆ (14-40%) [40] and MAPbBr₃ (16.4%) [15]. Further, CCE was gradually increased from 50% to 275% with the dose rate decreased from 532.4 nGy·s⁻¹ to 72.5 nGy·s⁻¹, as shown in Fig. 4(c). This phenomenon is generally observed in photoconductive photodetectors, carriers gradually fill into shallower traps with smaller gain while the irradiation intensity increases, which is known as the dynamic-range enhancing gain compression [41].

Fig. 4. (a) The on-off curves of X-ray detector based on Cs₂TeI₆ crystal under an X-ray beam bias of 40 kVp and under the X-ray illumination of dose changing from 72.5 to 532.4 nGy⁻¹·s⁻¹. The insert is dose rate-dependent signal-to-noise of Cs₂TeI₆ detector. The dashed line represents a SNR of 3. (b) Dose rate dependent current density of Cs₂TeI₆ detector. (c) Charge collection efficiencies of Cs₂TeI₆ detector, which decrease with increasing the dose rate.

The time-of-flight (TOF) technique was adopted to evaluate the carriers transport behavior of Cs₂TeI₆ crystal. When Cs₂TeI₆ detectors were irradiated by ²⁴¹Am 5.49 MeV alpha particles, electrons and holes can drift under positive and negative voltages, respectively, and the preamplifier signals were collected to obtain the carrier drift time. Fig. 5(a) and 5(c) demonstrate the average transient pulse spectra (normally,

10%-90% amplitude rise time of the spectra was selected) and the corresponding box statistic data distributions of rise time for the electron and hole under the bias voltage from 200 V to 550 V, respectively. The corresponding average rise time (τ) of electron and hole are in the range of 35-60 μ s and 20-50 μ s, respectively, and the rise time increases with the applied bias-voltage decrease from 550 to 200 V. The mobility (μ) could be obtained by:

$$\mu = \frac{v_{dr}}{E} = \frac{d^2}{V \cdot \tau} \quad (3)$$

where v_{dr} is the carrier drift velocity, E is the the electric field, d is the thickness of Cs_2TeI_6 crystal and V is the applied voltage. By linear fitting the plot of drift velocity vs. electrical field, as shown in Fig. 5(b) and 5(d), the mobilities of electron and hole are calculated to be $0.60 \pm 0.03 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ and $1.38 \pm 0.02 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$, respectively. The higher electronegativity of Te^{4+} increased the covalency of Te-I bonding of $[\text{TeI}_6]^{2-}$ octahedral units, which likely increases the formation energy of native defects V_I in Cs_2TeI_6 . The native defects are likely to behave as deep trap states for charge carriers, which account for the quite low mobilities of electron and hole of Cs_2TeI_6 [25].

Fig. 5. (a), (c) ^{241}Am α particle induced pulse and the corresponding distribution of the rise time of the electron and hole under various applied biases, respectively. (b), (d) The electrical field strength-dependent drifting velocities of electron and hole, respectively.

4. Conclusions

Pure lead-free perovskite Cs_2TeI_6 was synthesized and single crystal ingot of Cs_2TeI_6 with the dimension of $\Phi 10 \text{ mm} \times 55 \text{ mm}$ was grown by the vertical Bridgman method. The rocking of the crucible and hold at 400°C for homogenization during the synthesis process help to obtain the pure Cs_2TeI_6 polycrystals. Cs_2TeI_6 crystal

possesses $Fm-3m$ structure with the lattice parameter of $a=11.7137(8)$. The as-grown Cs_2TeI_6 crystal exhibits a high resistivity of $9.92 \times 10^{11} \Omega \cdot \text{cm}$, ascribed to the high formation energy of native defect iodine vacancies, which further resulted in the quite low mobilities of $0.60 \pm 0.03 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ and $1.38 \pm 0.02 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ for electron and hole, respectively. However, the X-ray sensitivity of Cs_2TeI_6 detector is $27.8 \mu\text{C} \cdot \text{Gy}^{-1} \cdot \text{cm}^{-2}$ under $2.76 \text{ V} \cdot \text{mm}^{-1}$ with the detection limit as low as $72.5 \text{ nGy} \cdot \text{s}^{-1}$, which was ascribed to the large gain (275%) and low noise current.

TOC

Associated content

Supporting Information

Calibration of the X-ray dose rate, the calculated signal-to-noise ratio and the average attenuation efficiency.

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Notes

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