X-ray detectors are broadly utilized in medical imaging and product inspection. Halide perovskites recently demonstrate excellent performance for direct X-ray detection. However, ionic migration causes large noise and baseline drift, limiting the detection and imaging performance. Here we largely eliminate the ionic migration in cesium silver bismuth bromide (Cs$_2$AgBiBr$_6$) polycrystalline wafers by introducing bismuth oxybromide (BiOBr) as heteroepitaxial passivation layers. Good lattice match between BiOBr and Cs$_2$AgBiBr$_6$ enables complete defect passivation and suppressed ionic migration. The detector hence achieves outstanding balanced performance with a signal drifting one order of magnitude lower than all previous studies, low noise (1/f noise free), a high sensitivity of 250 µC Gy$^{-1}$ cm$^{-2}$, and a spatial resolution of 4.9 lp mm$^{-1}$. The wafer area could be easily scaled up by the isostatic-pressing method, together with the heteroepitaxial passivation, strengthens the competitiveness of Cs$_2$AgBiBr$_6$-based X-ray detectors as next-generation X-ray imaging flat panels.
X-ray detection is significant for medical imaging, security inspection and nondestructive examination of industrial goods etc.1. Recently, metal halide perovskites have demonstrated excellent X-ray detection performance, due to the high X-ray attenuation coefficient, defect tolerance nature, and large mobility-lifetime product ($\mu\tau$)$^{2-5}$. Huang and co-workers pioneered the use of MAPbBr$_3$ single crystals for X-ray detection and achieved an impressive sensitivity of 21000 µC Gy$^{-1} \text{ cm}^2 \text{ cm}^{-2}$ toward 8 keV X-rays$^{3,4}$. Park and co-workers reported the flat-panel detectors utilizing printable CH$_3$NH$_3$PbI$_3$ films, obtaining a spatial resolution of 3.1 line pair per millimeter (lp mm$^{-1}$)$^6$. In parallel, in order to address the lead toxicity issue, we advocated Cs$_2$AgBiBr$_6$ as a promising non-toxic alternative with similar key features as lead halide perovskites, including a large $\mu$ product of about 10$^{-3}$ cm$^2$ V$^{-1}$s$^{-1}$, high X-ray absorption coefficient and larger resistivity ($10^9$ to $10^{11}$ Ω cm)$^7$. Cs$_2$AgBiBr$_6$ single crystal-based detector achieved a moderate sensitivity of 105 µC Gy$^{-1} \text{ cm}^2 \text{ s}^{-1}$ and a low detection limit of 59.7 nGy$^{-1} \text{ s}^{-1}$, which is comparable to the best-performing lead halide X-ray detectors$^3-6,8$. The spatial resolution reaches 4.9 lp mm$^{-1}$ at 20% modulation transfer function value. Taken together, our work showcases that Cs$_2$AgBiBr$_6$ wafer-based X-ray detectors are promising for next-generation X-ray imaging flat panels with features of stable output, low noise, high resolution, area scalability, and non-toxicity.

**Results**

**Preparation of Cs$_2$AgBiBr$_6$ wafers.** Currently, it is still a great challenge to prepare large-area and millimeter-thick perovskite films for imaging applications. In a typical solution process, the inevitable solvent evaporation leaves behind amounts of pinholes within the thick film. The remaining pinholes severely hinder the charge transport and decrease the imaging resolutions, which is the case for previous MAPbI$_3$-based X-ray imaging panels$^6$. In addition, for Cs$_2$AgBiBr$_6$, the generally adopted solvent, HBr acid solution, is highly corrosive and narrows the selectable substrate for fabricating flat-panel detector arrays$^{9-11}$. Thereby, we turn to an isostatic-pressing method for Cs$_2$AgBiBr$_6$ film fabrication$^5$, which involves no solvent during the process and produces a pinhole-free and compact Cs$_2$AgBiBr$_6$ wafer, as shown in Fig. 1a.

If CsBr, AgBr, and BiBr$_3$ were used as the precursors, we could sometimes observe the competitive phases of AgBr, Cs$_2$AgBr$_3$, Cs$_2$AgBi$_2$Br$_7$, and Cs$_3$Ag$_2$Br$_9$ in the wafer especially for low-temperature annealing conditions, as shown in Supplementary Fig. 1. Hence, we directly utilized Cs$_2$AgBiBr$_6$ powders as the precursor to ensure phase purity. The powders were firstly ball-milled through Cs$_2$AgBiBr$_6$ single crystals, resulting in grain sizes between 100 nm and 1 µm (Supplementary Fig. 2). The use of Cs$_2$AgBiBr$_6$ single crystals as raw materials also helps guarantee the low defect states within the bulk. The powders were then molded into a pie shape through a compressor and were subsequently subjected to a pressure of 200 MPa through a hydraulic press. The isotropic high pressure renders the wafer firmly flat and compact, leaving no pinholes within it. The pressing process is schematically shown in Fig. 1a. Here we prepared wafers with diameters of 5, 3, and 1 cm, producing an area of 19.62, 7.06, and 0.78 cm$^2$, respectively, demonstrating the upsampling capability of this method (Fig. 1b). Further increase of the wafer size could be obtained by larger models. The thickness is set as 1 mm, which is enough for X-ray attenuation$^7$. After pressing, the wafer was directly annealed at 350°C for 20 h to promote grain growth. The fabricated wafer exhibits a pure Cs$_2$AgBiBr$_6$ phase without any other impurity (Supplementary Fig. 3). As shown in Fig. 1c, SEM shows a homogeneous and dense surface. The cross-sectional SEM shows a compact, pinhole-free composition (Fig. 1d). The grain size reaches hundreds of micrometers, as shown in the inset image as well as Supplementary Fig. 4, much larger than the powders (100 nm

Here we demonstrate the fabrication of Cs$_2$AgBiBr$_6$ wafer, suppression of ionic migration via in situ heteroepitaxial growth of BiOBr, and sensitive and stable X-ray imaging applications. An isostatic-pressing method was used to synthesize Cs$_2$AgBiBr$_6$ wafers with upsampling capability, satisfying the requirements for large-area imaging applications. Thanks to the good lattice match between BiOBr and Cs$_2$AgBiBr$_6$ as well as convenient in situ formation of BiOBr, the epitaxial BiOBr serves as passivation layers and physical barriers to suppress the defects at grain boundaries and eliminate ionic migrations, as evidenced by that the measured activation energy of ionic migration for Cs$_2$AgBiBr$_6$ polycrystalline wafer is even slightly higher than Cs$_2$AgBiBr$_6$ single crystals and other lead-based perovskites. The about 20 cm$^2$ Cs$_2$AgBiBr$_6$ wafer-based detector exhibits low noise (1/f noise free), a high sensitivity of 250 µC Gy$^{-1} \text{ cm}^2 \text{ s}^{-1}$, a signal drifting three orders of magnitude lower than all previous perovskite X-ray detectors$^{3-6,8}$. The spatial resolution reaches 4.9 lp mm$^{-1}$ at 20% modulation transfer function value. Taken together, our work showcases that Cs$_2$AgBiBr$_6$ wafer-based X-ray detectors are promising for next-generation X-ray imaging flat panels with features of stable output, low noise, high resolution, area scalability, and non-toxicity.
could enhance the crystallinity and grain growth.

The distance between the neighboring Cs\textsubscript{2}AgBiBr\textsubscript{6} (001) plane. The distance between the neighboring ions in BiOBr is equal to its lattice parameter along x or y-axis, i.e., 3.915 Å, while the distance between neighboring Br\textsuperscript{−} in Cs\textsubscript{2}AgBiBr\textsubscript{6} is \( \frac{3}{4} a = 3.977 \) Å. The lattice mismatch is then derived as 1.6%, and such small mismatch ensures the compatibility of these two species.

Based on the above analysis, we added slightly more BiBr\textsubscript{3} into the Cs\textsubscript{2}AgBiBr\textsubscript{6} powders before isostatic pressing. The wafers were then thermally treated at 350 °C in the air atmosphere, and the moisture in the air could react with the excessive BiBr\textsubscript{3} to form BiOBr. It should be noted that the melting point of BiBr\textsubscript{3}, CsBr, AgBr is 218, 636, 432 °C, respectively. The thermal treatment at 350 °C could melt BiBr\textsubscript{3} and the melted ions are beneficial for defects repairing within the films. The mass ratio of BiBr\textsubscript{3}/Cs\textsubscript{2}AgBiBr\textsubscript{6} in the precursor was optimized as 1%, while the further increase would block the carrier transport. As shown in Fig. 2a, we could clearly see the characteristic diffraction peaks of BiOBr, and there is no BiBr\textsubscript{3} remaining in the products, verifying the complete reaction of BiBr\textsubscript{3} after thermal annealing.

Besides, the full width half maximum (FWHM) corresponding to 001 diffraction reached 0.064°, which is nearly identical to the 0.061° of Cs\textsubscript{2}AgBiBr\textsubscript{6} single crystal\textsuperscript{7}, confirming its high crystallinity. The representative cross-sectional SEM image of the wafer is shown in Fig. 2b, and the grain size is 30 to 100 μm after BiOBr introduction, similar to the wafer without BiOBr passivation (Supplementary Fig. 4f). The sheet-structured BiOBr could be clearly observed on the surface of the wafer (inset of Fig. 2b), further confirming the presence of BiOBr.

TEM characterization is used to verify the heteroepitaxial growth between BiOBr and Cs\textsubscript{2}AgBiBr\textsubscript{6}. It is difficult to record images at high-resolution mode due to the easy decomposition of Cs\textsubscript{2}AgBiBr\textsubscript{6} under strong electron beam radiation\textsuperscript{24}. Thereby the study was conducted at a low accelerating voltage, and the composition and structure were determined with energy dispersive spectroscopy (EDS) and selected area electron diffraction (SAED). As demonstrated in Fig. 2c, we located an area to 1 μm) in the precursor, which indicates substantial grain growth during isostatic pressing and thermal annealing process. The grain growth stems from the ionic nature of Cs\textsubscript{2}AgBiBr\textsubscript{6} and crystal plasticity\textsuperscript{5}. The increased grain size is beneficial for efficient carrier transport and charge collections.

**Structure analysis of Cs\textsubscript{2}AgBiBr\textsubscript{6} wafers.** Due to the polycrystalline nature, there are still amounts of residual grain boundaries within our Cs\textsubscript{2}AgBiBr\textsubscript{6} wafer. According to the knowledge of Pb-based perovskites, abundant halide vacancies present at the grain boundaries, which could serve as the ionic migration channels and lead to severe baseline drift\textsuperscript{22}. Similarly, our previous work demonstrates that bromide vacancies are also the major ionic migration channels for Cs\textsubscript{2}AgBiBr\textsubscript{6}\textsuperscript{7}. We indeed observed serious baseline drift for the wafer (will present later). Thereby the grain boundaries within the wafer have to be passivated to decrease the bromide vacancies and suppress ionic migration. As we stated previously, we believe epitaxial passivation is an effective route, like CdS passivation for CdSe, AlN for GaN and MAPbBr\textsubscript{3} for PbS\textsuperscript{12–14}. Here we find BiOBr as a suitable choice as heteroepitaxial passivation layer for Cs\textsubscript{2}AgBiBr\textsubscript{6}. BiOBr could be easily prepared by hydrolysis of BiBr\textsubscript{3} (also the precursor of Cs\textsubscript{2}AgBiBr\textsubscript{6}), guaranteeing the convenience and compatibility of the fabrication process.

Cs\textsubscript{2}AgBiBr\textsubscript{6} is the double perovskite, has a cubic structure, with the centers of metal bromide octahedron occupied by Bi\textsuperscript{3+} and Ag\textsuperscript{+}. The lattice parameter of Cs\textsubscript{2}AgBiBr\textsubscript{6} is \( a = b = c = 11.2499 \) Å. BiOBr crystallizes in the tetragonal matlockite structure (space group of P4/nmm), a layered structure with \[ \text{Bi}_2\text{O}_2 \] slabs interleaving by double slabs of halogen atoms\textsuperscript{23}. The lattice parameters of BiOBr are \( a = b = 3.915 \) Å, \( c = 8.07 \) Å. Each Bi\textsuperscript{3+} could be seen as coordinating with four Br\textsuperscript{−} ions and four O\textsuperscript{2−} ions. In terms of structure compatibility, the arrangement of Br\textsuperscript{−} ions in BiOBr (001) plane is the same as those Br\textsuperscript{−} within the Cs\textsubscript{2}AgBiBr\textsubscript{6} (001) plane. The distance between the neighboring two Br\textsuperscript{−} in BiOBr is equal to its lattice parameter along x or y-axis, i.e., 3.915 Å, while the distance between neighboring Br\textsuperscript{−} in Cs\textsubscript{2}AgBiBr\textsubscript{6} is \( \frac{3}{4} a = 3.977 \) Å. The lattice mismatch is then derived as 1.6%, and such small mismatch ensures the compatibility of these two species.
containing Cs, Ag, Bi, Br, O, Cu atoms, while Cs, Ag, Bi, and Br were from Cs₂AgBiBr₆ and Bi, Br, O came from BiOBr. Cu came from copper grids. The SAED shows that the selected area contains only one set of diffraction spots (Fig. 2d), demonstrating the single crystal nature. Based on the diffraction spots, the lattice fringes could be calculated as 3.94 Å and 5.46 Å, which is consistent with inter-distance (220) and (200) planes of Cs₂AgBiBr₆, and above values are just twice of the inter-distance of (200) and (110) planes in BiOBr. The inset in Fig. 2d shows the epitaxial growth model between Cs₂AgBiBr₆ and BiOBr crystals. We also observed the similar composition and SAED patterns in several other regions, verifying the epitaxial relationship between Cs₂AgBiBr₆ and BiOBr (Supplementary Fig. 5). The crystal structures of Cs₂AgBiBr₆ and BiOBr are depicted in Fig. 2e for structure compatibility comparison. As stated previously, Cs₂AgBiBr₆ can connect with BiOBr along [001] as {001}Cs₂AgBiBr₆ {001}BiOBr, which is further supported by the observed epitaxial growth of Cs₂AgBiBr₆ microcrystals onto BiOBr sheets (Supplementary Fig. 6).

**Optical and electrical properties of Cs₂AgBiBr₆ wafers.** From the above analysis, we conclude that BiOBr could indeed epitaxially grow onto Cs₂AgBiBr₆ crystals, and the presence of BiOBr is expected to suppress the surface defects at Cs₂AgBiBr₆ grain boundaries. The schematic model is shown in Fig. 3a. Br⁻ vacancies (V_Br⁻) are previously found as the main species accounting for ionic migration in Cs₂AgBiBr₆⁷. Here the presence of BiOBr could supply Br⁻ to suppress most of Br⁻ vacancies, thereby reducing the ionic migration channels and decreasing the ionic conductivity. To verify the influence of BiOBr passivation layer, we measured the resistivity of the wafers. As shown in Fig. 3b, after introducing BiOBr epitaxial layer, the wafer resistivity increased from 2.0 × 10⁸ to 1.6 × 10¹⁰ Ω·cm. The average resistivity of multiple Cs₂AgBiBr₆ wafers with BiOBr (1.4 × 10¹⁰ Ω·cm) is about five times higher than that of pristine Cs₂AgBiBr₆ (3.0 × 10⁹ Ω·cm). The resistivity enhancement is caused by the suppressed ionic conductivity and defects, as well as the insulating effect of BiOBr for electric conductivity. The higher resistivity is beneficial for achieving a declined dark current and thus abated noise current for the fabricated detectors.

To quantitatively characterize the ionic migration, we adopt the previously established method to directly extract the ion diffusion barrier⁷,25. The measurement details are shown in Supplementary Fig. 7 and Supplementary Note 1. In a nutshell, we exerted an exterior voltage to the crystal to direct the ionic diffusion, and the movable ions could accumulate at the border between Cs₂AgBiBr₆ and Au electrode. Upon turning off the voltage, the vacant positions of ion expeditiously migrated backward due to the concentration grade, resulting in an opposing current. The decay in the opposing current can utterly manifest the dynamics of the ion motion. Hence, the decay rate (k = r⁻¹), obtained by mono-exponential fitting, embodies the ion motion behaviors and is in proportion to the ion conductivity (σ_ion). By measuring the temperature-dependent current decays, the ion diffusion barrier can be obtained by fitting fitting ln(kt) versus 1/T. Figure 3c shows that Eₖ eff for BiOBr-passivated Cs₂AgBiBr₆ wafer is 360 meV, much higher than that of the pure Cs₂AgBiBr₆ wafer (203 meV) and even slightly higher than Cs₂AgBiBr₆ single crystals (348 meV), indicating the defects at
the grain boundaries have been perfectly suppressed by BiOBr passivation\textsuperscript{7,22}. Besides, the ion diffusion barrier of MAPbI\textsubscript{3} and MAPbBr\textsubscript{3} is only 134 and 127 meV according to the previous studies\textsuperscript{7,26}. The much higher diffusion barrier of BiOBr-passivated Cs\textsubscript{2}AgBiBr\textsubscript{6} wafer demonstrates its promising potential for ionic migration-free devices.

We also applied first-principle calculations to study the influence of BiOBr on ionic migrations of Cs\textsubscript{2}AgBiBr\textsubscript{6}. The detailed calculation processes are included in supplemental materials (Supplementary Figs. 8 to 18). In bulk Cs\textsubscript{2}AgBiBr\textsubscript{6}, the diffusion barrier of $V_{Br}$ is calculated as 0.30 eV, consistent with our previous result (0.33 eV)\textsuperscript{7}. On the bare surface of Cs\textsubscript{2}AgBiBr\textsubscript{6} (Fig. 3d), the diffusion barrier of $V_{Br}$ was slightly reduced to 0.25 eV, indicating that the Br vacancy migration is enhanced at the non-passivated Cs\textsubscript{2}AgBiBr\textsubscript{6} surface. Nevertheless, after passivation by BiOBr layers, the diffusion of $V_{Br}$ on the Cs\textsubscript{2}AgBiBr\textsubscript{6} surface (more precisely, on the Cs\textsubscript{2}AgBiBr\textsubscript{6}/BiOBr interface) is greatly suppressed, as its migration barrier is increased to 0.44 eV. For out-of-plane diffusion, we also calculated the barriers for $V_{Br}$ moving out of Cs\textsubscript{2}AgBiBr\textsubscript{6} as 0.56 eV, in the same Cs\textsubscript{2}AgBiBr\textsubscript{6}/BiOBr interface model (Fig. 3e). In addition, the $V_{Br}$ migration barrier of BiOBr itself is 0.99 eV, which is too high to allow any migration (Supplementary Fig. 16). Clearly, the presence of BiOBr can cut off $V_{Br}$ migration path and mitigate the ionic migrations, in addition to the passivation of defects at grain boundaries.

The $\mu$τ products have also been measured, while $\mu$ is the mobility of carrier and $\tau$ is the lifetime. The $\mu$τ product represents the distance that the carrier can transit under specific electric field strength. We employed a modified Hecht equation for fitting the
photoconductivity curve to extract $\mu r$ value.\(^{27,28}\) As exhibited in Fig. 3f, Cs$_2$AgBiBr$_6$ wafer without BiOBr passivation held a $\mu r$ product of $1.57 \times 10^{-3}$ cm$^2$ V$^{-1}$. After BiOBr introduction, the $\mu r$ product boosted to $5.51 \times 10^{-3}$ cm$^2$ V$^{-1}$. The increased $\mu r$ product, which can upgrade the extraction efficacy of photo-induced carriers, is due to the suppressed defects and increased carrier lifetime, the latter of which is verified by photoluminescence lifetime measurement. As shown in Fig. 3g, three processes were exhibited via the photoluminescence (PL) decay of pristine Cs$_2$AgBiBr$_6$ wafer: short (0.81 ns), intermediate (4.79 ns), and long (35.01 ns) lifetime components. The short and intermediate lifetime originate from surface-state emission, and the long lifetime as 63.05 ns.

In addition, we calculated for the density of states of the heteroepitaxial interface, there is no additional density of states introduced within the band gaps, confirming the good passivation effect of BiOBr (Fig. 3h). Also, the conduction band edge of BiOBr falls within the band gap of Cs$_2$AgBiBr$_6$. Cs$_2$AgBiBr$_6$ and BiOBr form a Type-II heterojunction (Supplementary Fig. 19), and the high carrier mobility of BiOBr guarantees the effective charge extraction.\(^{23}\) The presence of Type-II heterojunction and potential charge transfer could also contribute to the observed longer PL lifetime. The low ionic migration and good carrier mobility within BiOBr make the heterojunction structure highly resistant toward ion migration and conductive for carrier transport, which is supreme for X-ray detection applications.

X-ray detection and imaging. We now assemble the X-ray detector, where Au, Cs$_2$AgBiBr$_6$ wafer and Au vertically stack together. The device was illuminated by X-ray source employing a tungsten anode, the largest X-ray energy of which is 50 keV and the intensity climax is at 30 keV. We then calibrated the dose rate by a Radcal ion chamber dosimeter. It is noteworthy that the air ionization between cathode and anode electrodes could also contribute to the photocurrent. We subject the detectors into a vacuum trap to exclude the influence of air ionization.

The photocurrent response under an electric field of 0.1 V $\mu m^{-1}$ for Cs$_2$AgBiBr$_6$ wafer-based X-ray detectors is present in Fig. 4a and the dose rate is 138.7 $\mu Gy_{air}$ s$^{-1}$. The wafer passivated with BiOBr has a stable baseline and the dark current is about 1 nA. In contrast, the dark current keeps increasing for the pure Cs$_2$AgBiBr$_6$ wafer, and thus the signal reading becomes inaccurate. We also compare our results with previously reported perovskite-based X-ray and $\gamma$-ray detectors in terms of the applied electric field and dark current drift (Supplementary Table 1 and Supplementary Fig. 20). Clearly, the dark current drift of BiOBr-passivated Cs$_2$AgBiBr$_6$ wafer is $7.4 \times 10^{-5}$ nA cm$^{-1}$ s$^{-1}$ V$^{-1}$ under an electrical field of 0.5 V $\mu m^{-1}$, one order of magnitude lower than the best value of Pb-based perovskites ($1.4 \times 10^{-4}$ nA cm$^{-1}$ s$^{-1}$ V$^{-1}$)\(^{29}\) under a 50 times weaker electric field. The stabilization effect of BiOBr was due to the defect passivation and decreased ionic migrations. We then only calculate the sensitivity for BiOBr-passivated wafers. The measured photocurrent density scales linearly with the X-ray dose rate (Supplementary Fig. 21). The dose used here is the entrance dose in air and the electric field is 0.1 V $\mu m^{-1}$. A sensitivity of 32 $\mu C$ Gy$_{air}$ cm$^{-2}$ was derived for the wafer. The photocurrent responses under different electric field strengths and dose rates were also recorded (Supplementary Fig. 22). To compare the temporal rise behavior for the two devices, we conducted baseline subtraction for Cs$_2$AgBiBr$_6$ wafer in Fig. 4a. Then the response curves for Cs$_2$AgBiBr$_6$ and Cs$_2$AgBiBr$_6$ + BiOBr wafer were drawn together, showing similar temporal rise behavior (Supplementary Fig. 23). As the ion migration has been successfully suppressed by BiOBr passivation, then we record the detector sensitivity with...
the electric field ranging from 0.02 to 0.5 V µm⁻¹. As shown in Fig. 4b, the sensitivity linearly increased from 10 to 250 µC Gy⁻¹ cm⁻², which is twelve times higher than α-Se X-ray detectors (20 µC Gy⁻¹ cm⁻²) operating at a much higher field of 10 V µm⁻¹ [30]. The sensitivity of our polycrystalline wafer is even higher than the Cs₂AgBiBr₆ single crystal-based device (105 µC Gy⁻¹ cm⁻² at 0.025 V µm⁻¹). Previous Pb-based perovskites typically exhibit severe ionic migrations, excluding the use of large bias. We want to emphasize that high bias voltage is highly important for radiation detections, as it reduces the carrier transit time between electrodes, decreases the carrier diffusion length perpendicular to the electric field direction, and thereby prohibits the signal crosstalk between different pixels for imaging applications [31]. The imaging contrast result was shown in Fig. 4c. Stacking ITO glasses serve as X-ray attenuators, and the numbers represent the layers. The photocurrent decreases exponentially with the increase of stacking layers. We could derive the attenuation coefficient as 1.41 cm⁻¹ for ITO glasses, which is consistent with the theoretically calculated attenuation coefficient (1.42 cm⁻¹). Detection limit is a very important parameter to evaluate the device performance. By using the IUPAC standard of signal-to-noise ratio of 3, the detection limit of Cs₂AgBiBr₆ + BiOBr wafer is measured as 95.3 nGyair s⁻¹, which is slightly worse than our previous Cs₂AgBiBr₆ single crystal detector (59.7 nGyair s⁻¹) but much lower than 571.3 nGyair s⁻¹ of Cs₂AgBiBr₆ wafer (Supplementary Fig. 24).

Then we investigated the imaging capability of the fabricated detectors. The well-acknowledged slanted-edge method was adopted for the modulation transfer function (MTF) measurement, i.e., imaging the sharp edge of the line pair card with a single pixel [32]. The details are shown in Supplementary Fig. 25 and Supplementary Note 2. The pixel size was 200 µm × 200 µm, and the line pair card was fixed on an x–y scanning stage and transport along the direction of y axis for acquiring the edge imaging. The response for the edge was recorded as the edge spread function (ESF), and the ESF was then differentiated to produce the line spread function (LSF), as shown in Supplementary Fig. 25. The MTF could be derived by applying a fast Fourier transformation to the LSF. The detailed calculation process of MTF is shown in supporting information. The resulting MTF is presented in Fig. 4d, and the resolution is about 4.9 lp mm⁻¹ at 20% MTF value, which is higher than previous MAPbI₃-based imaging system (3.1 lp mm⁻¹) [9]. We remark that the resolution of the detector is related to the pixel size, pinholes within the film and signal crosstalk. Our compact wafer and the use of high electric field all contribute to the enhanced spatial resolution.

For imaging application, noise is very important and hence the noise spectrum was also evaluated through a spectrum analyzer. The BiOBr-passivated Cs₂AgBiBr₆ wafers are dominated by 1/f noise in the low-frequency region, which is probably caused by the presence of surface traps on the wafer (Supplementary Fig. 26). Here we introduced polyimide (PI) as an interface layer between perovskite and gold electrodes. It is found that the resulted noise power density (3.62 × 10⁻¹² A Hz⁻¹/2) is independent on frequency ranging from 1 to 1000 Hz with basically preserved device sensitivity (Supplementary Fig. 27), which may result from the full passivation of surface traps on the wafer by a thin PI layer (Supplementary Fig. 28). The shot noise and thermal noise were calculated as 2.83 × 10⁻¹⁵ and 2.88 × 10⁻¹⁶ A Hz⁻¹/2, respectively. The total white noise was then calculated as 3.12 × 10⁻¹⁵ A Hz⁻¹/2 by including shot noise and thermal noise, close to the measured result (Fig. 4e). The suppressed 1/f noise enables the use of low modulation frequency (1 or 30 frame per second) for signal reading. The uniformity of dark current and photocurrent is decisive on imaging quality. According to the acknowledged regulation, X-ray image should not have obvious artefacts, and the ratio of the standard deviation to the mean signal should be <10% [33]. Herein the pixel uniformity was measured within a 6 × 6 pixel array selected from the fabricated array in Fig. 5a, with the average value of dark current as 1003 ± 7 pA, and photocurrent as 1243 ± 15 pA, as shown in Fig. 5b. The ratio of standard deviation to the mean signal is calculated as 0.7% for dark current and 1.2% for photocurrent, which are an order of magnitude lower than the standard regulation. To further simulate the imaging performance of the wafer-based detector, a planar array was fabricated. The X-rays were detected by the detector after traveling through an iron ‘HUST’-shaped logo. The symbol ‘HUST’ was scanned and the recorded image is shown in Fig. 5c. We also assembled an eight-pixel linear array detector with a pixel size of 0.8 mm and a pitch of 0.8 mm (Fig. 5d). The pixels were connected to the electrometer. By linearly scanning in one direction, the heart-shaped logo could be easily distinguished. The spatial resolution could be further enhanced by integrating the fabricated wafers onto thin film transistor arrays with smaller pixel sizes (50 to 150 µm).

Discussion

One promising application of perovskite X-ray detectors is static/dynamic digital radiography (SDR/DDR), which requires the photoelectric conversion efficiency larger than 30 e⁻ keV⁻¹, and frame rates of 1 frame per second (FPS) for SDR or 30 FPS for DDR [34]. These are within the capability of perovskite X-ray detectors. Baseline drift, also well known as ‘polarization’, is a common difficulty for all kinds of direct X-ray detectors including α-Se, CdZnTe, and perovskites. Here the polarization issue has been resolved by the presented heteroepitaxial passivation method. One unaddressed issue for all reported perovskite X-ray detectors is the required dark current density lower than 10⁻¹⁰ A cm⁻³. This value is derived from the minimal dynamic range constraint: Qdark = Qsignal, Qdark is Idark × A × Δt, and Qsignal is εₚhoton/(2.8e₉ + 0.5 eV) from one X-ray photon, where A is the pixel area (typically 100 µm × 100 µm), Δt is charge read out time, εₚhoton is photon energy of X-ray (10 to 50 keV), P-N or Schottky junctions could be introduced to suppress the dark current. Moreover, charge-sensitive preamplifiers, with the characters of high gain and ultra-low noise (lower than 100 e⁻), are suitable back-end electronic components to further enhance the detector dynamic range and signal quality.

In conclusion, we utilized an isostatic-pressing method to prepare Cs₂AgBiBr₆ wafers with tunable sizes, achieving non-toxic, large-area and high-performance X-ray detectors for imaging. The epitaxial growth of BiOBr onto Cs₂AgBiBr₆ enables the perfect grain boundary passivation and helps suppress ionic migrations to single crystal level. The signal drifting of the detector is three orders of magnitude lower than all previous perovskite X-ray detectors. Device sensitivity reaches 250 µC Gy⁻¹ cm⁻² at 0.5 V µm⁻¹ bias, 12 times higher than α-Se detectors. The spatial resolution is about 4.9 lp mm⁻¹ at an MTF value of 0.2. Thanks to the high uniformity and low noise current, we built 6 × 6 pixel arrays on our Cs₂AgBiBr₆ wafer and explored their imaging application. Further optimizing the pixel configuration and assembling Cs₂AgBiBr₆ wafers onto thin film transistor arrays or CMOS chips would push them toward practical imaging applications. Overall, the combined features of low-cost fabrication, area scalability, non-toxicity, stable output and ultra-low noise strengthen the competitiveness of Cs₂AgBiBr₆-based X-ray detectors as next-generation X-ray imaging flat panels.
**Methods**

**Materials.** CsBr (99.9%) was purchased from Aladdin Reagent Ltd. AgBr (99.9%) and BiBr₃ (99%) were from Sigma-Aldrich. Hydrobromic acid (HBr, 40% wt/wt) was from Macklin, and 1-methyl-2-pyrrolidone (NMP, 99%) was purchased from Sinopharm. p-Phenylenediamine (97%) was from Macklin, 4,4’-bipthalic anhydride (BPDA, 99%) from J&K Scientific. All reagents were used as received.

**Cs₂AgBiBr₆ single crystals.** Cs₂AgBiBr₆ crystals were grown using an improved inverse temperature crystallization method. Specifically, CsBr (0.002 mol, 0.426 g), BiBr₃ (0.001 mol, 0.449 g), and AgBr (0.001 mol, 0.188 g) were added into HBr solution (12.5 mL) within a glass container. The container was heated to 110 °C to entirely dissolve the precursors. The solution was then cooled to 80 °C to promote crystal growth.

**Preparation of Cs₂AgBiBr₆ wafer.** Cs₂AgBiBr₆ crystals were firstly ball-milled for about five hours to achieve uniform Cs₂AgBiBr₆ powders. The powders were then mounted into a pie shape mold through a compressor, and subsequently were subjected to a pressure of 200 MPa through a hydraulic press (LDJ-100/320-300). By changing the mold, the wafer size could be readily modulated, and the targeting thickness could be obtained by adjusting the pressing pressure and precursor loading amount. The wafer was then annealed on the hot plate at 200 to 350 °C for 4 to 20 h in air for further crystallization, the optimized condition was 350 °C for 20 h.

**Device fabrication.** A 1-mm-thick Cs₂AgBiBr₆ wafer X-ray detector was employed for device assembly, where Au/Cs₂AgBiBr₆ wafer/Au stacked vertically. The Au electrodes (about 80 nm) were thermally evaporated. To suppress 1/f noise, we introduced polyimide (PI) as an interface layer between perovskite and gold electrodes. For 1% weight ratio of PI precursor preparation, 0.0336 g p-phenylenediamine and 0.0956 g BPDA were added into 12.6 mL NMP, and the precursor was blended for 8 h at room temperature and consecutively at 40 °C for 12 h. Then the precursor was drop-coated onto the surface of Cs₂AgBiBr₆ wafer, and then the solution was cured for 10 to 30 min on a 120 °C hot plate.

**Material characterization.** The crystal structure and phase purity of Cs₂AgBiBr₆ wafer were identified by X-ray diffraction (XRD, Philips, X pert pro MRD, Cu Ka radiation, λ = 1.54178 Å). Morphology of Cs₂AgBiBr₆ wafer was studied by SEM (FEI Nova NanoSEM450, without Pt coating). TEM was acquired through Tecnai-G2 20U-TWIN. Time-resolved photoluminescence was tested at 630 nm under a 478 nm light pulse as excitation from the HORIBA Scientific DeltaPro fluorimeter.

**Detector performance measurement and X-ray imaging.** X-ray tube with tungsten anode (HAMAMATSU L9421-02) was used as the source. The X-ray focal spot size is 5 μm. A Keithley 6517B provided the bias voltage and recorded the response current. For noise currents measurement, 5 V bias was exerted onto the device by low noise current amplifier (SR570) and the output was coupled to lock-in amplifier (SR850). SR570 worked in high bandwidth mode (High BW) without any filter. The X-ray source was under a constant 50 kV voltage. The current was changed from 1 to 160 μA. Al foil (2 mm thick) was used as the attenuator between the X-ray tube and Cs₂AgBiBr₆ wafer. The dose rate has been evaluated with a Radcal ion chamber (model: 10 × 6 × 180) dosimeter. The measurement was operated in the dark and subjecting the device in vacuum to avoid the influence from visible light and air ionization. For acquiring X-ray imaging, the object was adhered on a X-Y scanning stage (Zolix PSA200–11-X), and we controlled the object to transport in the directions along x and y axis.

**Computational methods.** First-principle calculations were carried out using density functional theory, as implemented with the Vienna *Ab initio* simulation package...
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**Author contributions**

J.T. and G.N. supervised the whole project and conceived the idea. G.N., B.Y., W.P. and H.W. designed the experiments and analyzed the data. B.Y., W.P. and H.W. carried out most material characterizations and device optimizations. J.-H.Y. and K.-H.X. performed the theoretical simulation and analyzed the results. L.Y. and X.D. assisted in device optimization. X.M., X.Y. and Q.X. helped in detector performance discussion. G.N., B.Y., K.-H.X. and J.T. wrote the paper; all authors commented on the manuscript.

**Additional information**

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