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Two-Step Vapor Deposition of Self-Catalyzed Large-Size PbI₂ Nanobelts for High-Performance Photodetectors

Mingming Han,†a Jiamin Sun,†ab Luozen Bian,†ab Zhou Wang,‡ Lei Zhang,§ Yanxue Yin,‡ Zhaofeng Gao,‡ Fulin Li,§ Qian Xin,§ Longbin He,§ Ning Han,*‡ Alimin Song§ and Zai-xing Yang*‡

The grown lead iodide (PbI₂) is usually two-dimensional sheets with a finite size which necessitate sophisticated device metallization and the growth of quasi one-dimensional materials is still challenging. In this work, large-size (length > 100 μm), single-crystalline and high-density PbI₂ nanobelts are successfully synthesized by manipulating the microenvironment in a two-step vapor deposition process at a slow heating rate of ~18 °C min⁻¹. Firstly, PbI₂ nanosheet seeds are grown by physical vapor deposition, and then PbI₂ nanobelts are synthesized by a self-catalyzed vapor-liquid-solid growth mechanism, which is verified by the Pb nanoparticles on the nanobelts tips. Photoemission spectra show the uniform high-quality crystallinity of the as-prepared large-size PbI₂ nanobelts with a bandgap of 2.36 eV. When configured into photodetectors with a shadow mask, the fabricated device exhibits a low dark current of 4 nA, an impressive ON/OFF current ratio of 10² ~ 10⁶, a photoresponsivity of 13 mA W⁻¹, and a fast response with the rise and decay time constants of 425 and 41 ms, respectively. All these performances are comparable to those of state-of-the-art of layered PbI₂ nanostructures photodetectors, but the ease of synthesizing large-size PbI₂ nanobelts may have useful impact on next-generation easily-fabricated high-performance optoelectronics.

Introduction

In the past decade, layer-structured materials with in-plane covalent bonding and weak interlayer interactions (van der Waals) have attracted extensive research attentions, owing to the possibility of thinning down to atomically thick two-dimensional (2D) materials.¹⁻¹³ As a typical layered perovskite derivative, lead iodide (PbI₂) has attracted extensive research attention in solar cells, photodetectors and other optoelectronic devices,¹⁴⁻²⁶ due to its direct bandgap of 2.28-2.5 eV and tunable optoelectronic properties.¹⁴⁻¹⁷ Layered PbI₂ material is composed of covalently bonded I-Pb-I repeating units stacked along the c-axis by van der Waals interlayer interaction.¹⁸⁻²⁰ Up to now, low dimensional PbI₂ nanostructures of nanosheets,¹⁹⁻²², ²⁴, ²⁶ nanowires,²⁵⁻²³, ²⁷ and atomically thin monolayers²² have been prepared by a simple synthesis method of vapor deposition. In the reported vapor deposition of PbI₂ nanostructures, one-dimensional (1D) nanowires followed a chemical vapor deposition (CVD) process,¹⁹, ²³⁻²⁷ otherwise, two-dimensional (2D) nanosheets followed a physical vapor deposition (PVD) process.¹⁹, ²¹⁻²³, ²⁶ For example, Meyers et al. reported recently the self-catalyzed vapor-liquid-solid (VLS) growth of PbI₂ nanowires in a CVD growth procedure.²³ On the other hand, highly uniform 2D PbI₂ nanosheets have been prepared by Wang et al. via a space confined PVD process.²⁶ Furthermore, Lan et al. pointed out that the surface roughness of the growth substrates played a critical role on the nucleation of PbI₂ microplanes in a PVD growth of 2D PbI₂ nanosheets.²¹ However, for photodetector application, 1D nanowires have a relatively smaller absorption area leading to low current density and 2D nanosheets with a finite size necessitate complicated device metallization such as Au nanowire mask method.¹⁹, ²² Therefore, it is highly desirable to synthesize large-size 2D materials for easily fabricated photodetectors.

Combining the geometry of 1D nanowires with 2D nanosheets, quasi 1D nanostructure of 2D nanobelt is considered as a promising candidate for achieving high performance and easily fabricated optoelectronic devices. Up to now, most of the works are concentrated on the 2D morphologies with grain size on the order of tens of micrometers,¹⁹, ²², ²⁴, ²⁶ there are limited reports focusing on the large-scale synthesis of 2D PbI₂ nanobelts with size up to hundreds of micrometers in a CVD process. With a size up to hundreds of micrometers, it will become easy to handle the authentic optoelectronic applications of 2D nanomaterials. In this work, large-scale PbI₂ nanobelts with length up to hundreds of micrometers (>100 μm) have been prepared successfully on amorphous SiO₂/Si substrates via a...
two-step thermal evaporation process. Firstly, the hexagonal layered PbI₂ nanosheets are formed on the growth substrate when the source material of PbI₂ is at a low thermal temperature, following a PVD growth process. With the increase of the heating temperature, PbI₂ nanobelts grow from the as-grown PbI₂ nanosheet seed layer by a self-catalyzed CVD process. The mass of the source material, growth temperature and growth time are found to be the essential issues on the controllable growth of large-size and high-density PbI₂ nanobelts. Without adopting any sophisticated device fabrication process, the as-prepared lager-size PbI₂ nanobelts can be configured into the simple photoconductors by shadow mask, exhibiting impressive photosensing properties with a small dark current of 4 pA, an impressive ON/OFF current ratio of 10⁵ ~ 10⁶, and a good responsivity of 13 mA W⁻¹ at a wavelength of 445 nm, an excellent stability and an efficient time response (i.e., rise and decay time constants of 425 and 41 ms, respectively). All these results confirm evidently the technological potency of these large-size and highly crystalline 2D PbI₂ nanobelts for easily-fabricated high-performance photodetectors.

Experimental

PbI₂ nanobelts synthesis

Large-size PbI₂ nanobelts studied here were synthesized by employing a solid-source CVD method in a horizontal tube furnace, similar to the reported literatures. In brief, the solid source of PbI₂ powder (99.99% purity) was located in the upstream and the growth substrate of SiO₂/Si was located in the downstream of a two-zone tube furnace with a distance of 5.5 cm. Argon (99.999% purity) was used as the carrier gas to transport the thermally vaporized material to the downstream. Prior to heating, the quartz tube was purged with 50 standard cubic centimeter (sccm) Ar for 0.5 h. During growth, the source material of PbI₂ was heated to 550 °C in 30 min (~ 18 °C min⁻¹) and was kept at this temperature for 20 min. As shown in the temperature distribution of downstream zone (Fig. S1, ESI†), the growth temperature of the large-size PbI₂ nanobelts is deduced as ~ 364 °C. After growth, heating of PbI₂ was stopped and cooled to room temperature naturally in the Ar flow. Eventually, a layer of orange yellow product could be collected on the substrate.

Materials characterization

Surface morphologies of the as-grown large-size PbI₂ nanobelts were examined using a scanning electron microscope (SEM, Nova NanoSEM 450, FEI Company) and a transmission electron microscope (TEM, FEI Tecnai 20). The thickness of the as-prepared large-size PbI₂ nanobelts were measured by atmoic force microscope (AFM, CSM55000, Being Nano-Instruments). The crystal structure and crystallinity of the products were verified by X-ray diffraction (XRD, D8 Advance, Bruker) and selected area electron diffraction (SAED) attached to TEM. Elemental identifications were performed using an energy dispersive x-ray spectroscopy (EDS) detector attached to SEM to measure the chemical composition of the obtained nanobelts.

For the TEM studies, the nanobelts were scratched onto the copper grid for the corresponding characterization. Raman and Photoluminescence (PL) spectra followed PL and Raman mappings were measured by a Raman spectrometer (inVia Reflex, Renishaw) with 532 nm laser and 325 nm laser, respectively. Corresponding absorption spectrum was measured using UV-vis spectrometer (TU-1901, Beijing Puxiongong Company), which was converted to absorbance spectra (α = -ln(r), where B is a film thickness related coefficient).

Nanobelts devices fabrication and photo-electrical property measurements

For the device fabrication, the nanobelts were firstly transferred onto the degenerately doped p-type Si substrates with a 300 nm thick thermally grown gate oxide layer by using a physical dry transfer technique. Stainless steel grid was next used as the shadow mask and attached onto the substrate. Ti (5 nm) and Au (200 nm) thin films were deposited via electron beam evaporation as the electrical contact electrode. The electrical performance of the fabricated device was then characterized with a standard Lakeshore electrical probe station and a Keithley 4200 semiconductor analyzer. Laser diodes with wavelength of 375, 445, 532, 630 and 730 nm were used as light source for the photodetector measurement, while the power of the incident irradiation was tuned and measured using a power meter from 15 to 150 mW cm⁻².

Result and discussions

SEM together with EDS technology are adopted here to characterize the morphology and composition of the as-prepared lager-size PbI₂ nanobelts. With an optimal growth condition of 0.015 g PbI₂ powder as source material, lager-size PbI₂ nanobelts with high density have been prepared successfully on amorphous substrate at 550 °C for 20 min in a 50 sccm Ar atmosphere. As shown in Fig. 1a, the as-grown sample shows a morphology of nanobelt with a smooth surface and a length of >100 µm. A good response of the large-size PbI₂ nanobelts is also verified by TEM in Fig. 1b. As shown in Fig. 1d, the thickness of the as-prepared large-size PbI₂ nanobelts is measured as 287 ± 94 nm by AFM. Furthermore, the smooth surface of the as-prepared PbI₂ nanobelts is also verified by TEM in Fig. 1b. SAED pattern in the inset displays the characteristic hexagonal symmetry of diffraction spots with the zone axis of [0001], suggesting that the nanobelts are grown in the <01 0 0> direction with an excellent crystallinity. Based on the XRD pattern of Fig. 1c, the as-prepared PbI₂ nanobelts is the hexagonal PbI₂ structure (JCPDS: 07-0235) without any other impurity phases, indicating the nanobelts being pure PbI₂ crystals. This is in line with the SAED result. It is worth pointing out that nanospheres are found at the tip of the as-prepared nanobelts (Fig. 1d), indicating the as-prepared nanobelts follow a VLS growth mechanism. It is a common phenomenon of nanoparticles existing on the as-prepared PbI₂ nanobelts, as shown in Fig. S3,
ESI.†. The sizes of the observed nanoparticles are 200-1200 nm. The detailed growth mechanism of this kind of large-size PbI₂ nanobelts will be discussed later. As presented in Fig. 1e & f, the EDS elemental mapping of the same nanobelts (inset of Fig. 1d) illustrates the homogeneous distribution of Pb and I atoms along the nanobelts body. In the meanwhile, it is found that the tip mainly contains Pb atom, whereas the I content drops drastically once passing the tip/nanobelt interface, as shown in Fig. S4, ESI.†. In short, all these demonstrate the well-controlled surface morphology, crystallinity and stoichiometry of PbI₂ nanobelts achieved with a simple vapor deposition growth technique.

For guiding the controllable growth of large-size 2D nanomaterials, the growth mechanism of the as-prepared PbI₂ nanobelts is studied in detailed by issues of the mass of source material, growth temperature, and growth time. As shown in SEM images of Fig. 2, one can see that the mass of PbI₂ plays an important effect on the as-prepared PbI₂ morphology. With a low content of 0.005 g PbI₂ powder, only nanosheets are found on the substrate. When the mass of PbI₂ powder reaches 0.01 g, large-size PbI₂ nanobelts with low density can be observed, possibly caused by the inadequate PbI₂ or Pb/I vapor during the nanobelt growth process. Afterwards, as the mass of PbI₂ powder exceeds the optimal content of 0.015 g, there are small nanosheets grow on the surface of the large-size PbI₂ nanobelts, as marked by red circles in Fig. 2c&d. In a word, as PbI₂ has a relatively low melting point of 406 °C,35 it evaporates easily to form the vapor phase precursors. Therefore, too little source such as 0.005 g would be all evaporated to form the nanosheets, leading to no successive nanobelt growth. While higher source mass would provide not only the precursors for nanosheet but also the nanobelt growth. On the other hand, the effect of growth temperature on the controllable growth of PbI₂ nanobelts is also studied and the corresponding morphology can be found in Fig. S5, ESI.†. Namely, at a low growth temperature of 490 °C, nanosheets dominated the morphology of the as-grown sample. With the increase of growth temperature, the amount of nanobelts increases. However, the width of these as-grown nanobelts is narrow, possibly caused by the inactive PbI₂ or Pb/I vapor. In the end, the growth time is also found to be a significant element on the controllable growth of large-size PbI₂ nanobelts, as shown in Fig. 3. With a growth time of 1 min, nanosheets together with very short nanobelts are observed on the substrate. When the growth time prolongs to 5 min, large-size PbI₂ nanobelts with very low density are prepared. Importantly, with a high-resolution SEM images, one can see that the nanobelts are grown from the nanosheets randomly. That is, some nanobelts are parallel to the nanosheets and the others are tilted to the nanosheets. The tilt angle can be estimated from XRD pattern in Fig. 1c, where the dominant peaks are related to c-plane of PbI₂ while only a weak peak attributed to (201). Therefore, it is plausible that most nanobelts tilt at an angle of ~75° which is the one between (201) and (001) planes. It is worth pointing out that the success control growth of the large-size PbI₂ nanobelts is benefited from the slow heating rate (reach 550 °C in 30 min) of the source material. With a rapid heating rate of the source material (reach 550 °C in 7 min), there are only nanoparticles on the substrate (shown in Fig. S6, ESI.†). Anyway, this phenomenon of nanostructures growing from its seed layer is usually found in the growth process of other kinds of nanomaterials.36-39 In a word, by adopting an optimal growth condition of 0.015 g PbI₂ powder evaporated at 550 °C for 20 min, high-quality and large-size PbI₂ nanobelts with a high density can be prepared on the amorphous SiO₂/Si substrate.

Based on the above discussion, a possible growth mechanism can be proposed here, as shown in Fig. 3e-h. With a slow heating rate of source material, the growth of large-size PbI₂ nanobelts can be divided into two stages. At the first stage, PbI₂ nanosheets grow on the smooth substrate by a PVD process, as reported elsewhere.19, 21, 22, 26 Namely, at a low growth temperature, the new coming PbI₂ species would get adsorbed on the PbI₂ nuclei as well as on the substrate surface and then be migrated to the growth sites. Similar to the other types of layered materials, the growth sites of layered PbI₂ nanosheets are always located at the edges as illustrated in Fig. 3e. As a
result, PbI₂ nuclei would then be expanded in the in-plane direction and grown into a large sheet-like structure, as shown in Fig. 3f. With the increase of growth temperature, the evaporated PbI₂ would mostly be decomposed into elemental or molecular Pb and I species. Pb has a higher boiling point of 1749 °C,⁴ but a low melting point of 327.4 °C,⁴⁰ therefore, it is possible for Pb species to aggregate into Pb liquid droplets during the growth. This result has been verified by the EDS mapping of the as-prepared PbI₂ nanobelts in Fig. 1e-f. Consequently, the PbI₂ nanobelts can then be grown after the catalytic supersaturation of PbI₂ in the Pb liquid droplets via VLS mechanism. However, with a rapid heating rate of source material, there is not abundant time for the PVD growth of seed layer of PbI₂ nanosheets on the substrate, and thus no nanobelts can be prepared (Fig. 5e, S5a, ESI†). With a low content of source material, PbI₂ powder would be evaporated off at the first stage of nanosheets growth, resulting in insufficient source vapor for the nanobelts growth. In this case, only nanosheet can be found on the substrate, as shown in Fig. 2a. With an excessive source material, the third PVD/CVD growth process of PbI₂ nanobelts started at the smooth surface of the as-grown large-size PbI₂ nanobelts. As a result, many irregular nanosheet/nanobelts are observed on the surface of the large-size nanobelts (shown in Fig. 2c&d). In case of growth temperature, only PVD growth process occurs at a low growth temperature, and the as-prepared sample shows nanosheets with a few of nanobelts (shown in S5a, ESI†). However, with the increase of growth temperature, the decomposition of PbI₂ occurred and the contents of Pb and I vapor increase simultaneously, resulting in the success growth of large-size PbI₂ nanobelts (shown in Fig. S5b-d, ESI†). In short, with a slow heating rate of source material, high-quality, high-density and large-size PbI₂ nanobelts have been prepared successfully from a seed layer of PbI₂ nanosheets by a VLS growth mechanism in a two-step thermal evaporation process.

Raman, UV-vis absorption and PL spectra are carried out to investigate the optical properties of the as-prepared large-size PbI₂ nanobelts. The Raman data of the PbI₂ nanobelts excited by a 532 nm wavelength laser is recorded in Fig. 4a. Three dominant Raman peaks are clearly observed at the location of 73.8, 97.2, and 112.7 cm⁻¹, corresponding to the E₂g, A₁g, and A₂u Raman vibration modes in 2H polytype of PbI₂, respectively.¹⁰,²⁶,⁴¹,⁴² Similar with the reported 2D PbI₂ nanostructures, the peak intensity of the as-prepared large-size PbI₂ nanobelts is strong and the corresponding peak’s full width at half-maximum (FWHM) is small,¹⁹,²²,²⁴,²⁶ indicating a high crystal quality. UV-vis absorption spectrum is employed to study the bandgap of the as-prepared large-size PbI₂ nanobelts. The experimental values of the bandgap can be obtained through a Kubelka-Munk (K-M) transformation of the UV-visible spectrum: \[ \frac{F(R)h\nu}{(F(R)h\nu)^2} \]

where F(R) is the diffuse reflectance spectrum.⁴³⁻⁴⁵ As shown in Fig. 4b, the calculated bandgap of PbI₂ nanobelts is about 2.36 eV, which coincides well with the previous reports.¹⁶,¹⁹⁻²²,²⁴,²⁷ In addition to Raman and UV-visible spectra, room temperature PL spectrum of the as-prepared large-size PbI₂ nanobelts is also obtained, as shown in Fig. 4c. The sharp peak centered at 514 nm (2.41 eV) is in perfect agreement with the bandgap of 2.36 eV determined from the UV-visible spectrum. The strong peak intensity and the narrow FWHM of the PL peak further verify the high crystalline quality of the as-grown large-size PbI₂ nanobelts. This result also can be deduced from the 2D PL mapping image of the as-prepared large-size PbI₂ nanobelts. As depicted in the inset of Fig. 4c, the color contrast of PL mapping is very uniform, indicating the uniform crystallinity of the large-size PbI₂ nanobelts. It is noticable to point out that there is no 2D PL mapping signal from the Pb nanoparticle, resulting in a black zone at the top of the as-prepared PbI₂ nanobelt, as shown in Fig. S7, ESI†. This phenomenon also can be found in 2D Raman mapping at a frequency of 97.2 cm⁻¹ (PbI₂ domain). However, in Fig. 4c, owing to the low resolution, the black sphere zone of the Pb nanoparticle is so small that it cannot be
seen clearly. In short, all these results strongly suggest the potential application of the as-prepared large-size PbI$_2$ nanobelts with high crystallinity for high-performance optoelectronic devices.

As a direct bandgap semiconductor, besides the understanding of growth kinetics and mechanisms, it is interesting to assess the optoelectronic properties of the as-prepared large-size PbI$_2$ nanobelts. In this case, photodetector is fabricated on the SiO$_2$/Si substrate by a simple shadow mask process (Si substrate with a 300 nm SiO$_2$ insulating top layer) and is electrically characterized under illumination. Fig. 5a is the SEM image of the as-fabricated photodetector with a PbI$_2$ nanobelt area of 879.8 $\mu$m$^2$. Inset is the atomic model of PbI$_2$ crystal, displaying PbI$_2$ is a layered material, which composed of covalently bonded I-Pb-I repeating units stacked along the c-axis and the van der Waals interlayer interaction. Fig. 5b is the device schematic of the as-fabricated photodetector. Under illumination, electron-hole will generate and transform in the semiconductors. As shown in Fig. 5b, ESI, the current linearly increase with the voltage in current-voltage (I-V) curves, indicating good Ohmic contacts between the Au electrodes and PbI$_2$ nanobelts. At a bias voltage of 5 V, the photocurrents of the as-fabricated photodetector are shown in Fig. 5c under different incident light wavelengths with an intensity of 35 mW cm$^{-2}$. With an illumination laser wavelength smaller than the bandgap of the as-prepared PbI$_2$ nanobelts (514 nm), the photocurrent increases with the increase of laser wavelength. On the other hand, no photocurrent can be detected when the illumination laser wavelength is larger than 514 nm. Hence, the 445 nm laser is selected to illuminate the photodetector for better understanding the photosensing behavior of the PbI$_2$ nanobelts. The dependence of its photocurrent on different light intensities is measured and depicted in Fig. 5d. It is well known that the measured data can be well fitted by Equation $I_p = \alpha \Phi^\beta$, where $I_p$ is the photocurrent, $\alpha$ and $\beta$ are the fitting parameters, and $\Phi$ is the light intensity.\textsuperscript{46-51} As a result, the as-fabricated photodetector reveals a power dependence of $I_p = 0.230^\beta$ from the fitting of the measured data, depicting the sublinear relationship between the photocurrent and light intensity, which is often observed in layer-based material based photoconductors due to the complex processes of electron-hole generation, trapping, and recombination in the semiconductors.\textsuperscript{46-48} It is worth to point out that the value of $\beta$ is higher than the reported 2D nanosheets in literatures,\textsuperscript{19,21,22} indicating the high crystallinity of the as-prepared PbI$_2$ nanobelts. Furthermore, two important figure of merits, responsivity (R) and detectivity ($D^*$), are the key parameters for

<table>
<thead>
<tr>
<th>Morphology</th>
<th>Light (nm)</th>
<th>Bias (V)</th>
<th>Dark current (pA)</th>
<th>On/off ratio</th>
<th>Rise time (ms)</th>
<th>Decay time (ms)</th>
<th>Reference</th>
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<tr>
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<td>445</td>
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<td>10$^1$</td>
<td>425</td>
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<tr>
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<td>1380</td>
<td>10$^2$</td>
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<td>10</td>
<td>10$^3$</td>
<td>18</td>
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<td>560</td>
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</table>
evaluating the sensitivity of the as-fabricated photodetector. R
is defined as the photocurrent generated per unit power of
incident light on the effective area of a photodevice, and D*
reflected the photodetector’s sensitivity. R and D* can be
analyzed by the following equations: R = I_p (OS)^-1 and
D* = rS^1/(2eln)^-1/2, where I_p is the photocurrent, OS is the light
intensity, S is the active area of the photodetector, e is the
absolute value of the charge of an electron, and ln is the base
current.\textsuperscript{52-55} For the large-size PbI\textsubscript{2} nanobelts based
photodetector, the maximum R and corresponding D* are
calculated to be 13 m\textsuperscript{2}A\textsuperscript{-1} and 3.048 \times 10\textsuperscript{12} Jones across
the entire measured range, respectively, comparable to the
graphene photodetectors (0.5–6.1 m\textsuperscript{2}A\textsuperscript{-1})\textsuperscript{56, 57} and the single-
crystal CdTe nanosheets (0.6 m\textsuperscript{2}A\textsuperscript{-1}).\textsuperscript{58} The repeatability and
response speed are another two essential parameters for the
performance assessment of photodetectors. The repeatability
can be appraised by measuring the photocurrent as a function of
time (i.e., I-t curves) under chopped illumination in Fig. 5e. It
is obvious that the device ON- and OFF-state can be effectively
modulated by the chopped illumination with a good
repeatability and an impressive ON/OFF current ratio of 10\textsuperscript{11} ~
10\textsuperscript{8}. It is worth to pointing out that the photodetector also has
a low dark current of 4 p\textsuperscript{A} when the laser is on the “OFF” state.
The low value of dark current indicates a low noise and a high
sensitivity, which are vital for the practical electric-devices.
In addition, a high-resolution I-t curve is then utilized to study the
response speed of the photodetector. Usually, the time needed
for the current to increase from 10% to 90% of the peak value
and vice versa are defined as the rise time and decay time
constants, respectively.\textsuperscript{59, 60} Based on the measurement
presented in Fig. 5f, the rise and decay time constants can be
identified as 425 and 41 ms accordingly, implying the high
quality of the as-prepared large-size PbI\textsubscript{2} nanobelts. Regardless,
all these obtained performance indicators of nanobelts
detectors are highly comparable to those of state-of-the-art
PbI\textsubscript{2}, as reported in the recent literature (Table 1), illustrating the
impressive performance and promising prospect of our larger-
size PbI\textsubscript{2} nanobelts for the high-efficient photodetection. It is
worth to pointing out that the rise and decay times are related to
the recombination of nonequilibrium photo-generated
 carriers. The combination processes can be affected by many
factors, such as trap density, trap energy level in the forbidden
gap, surface states, and adsorbed molecules, etc. Those factors
are not only related to the quality of the photosensing
materials, but also related to device fabrication processes.
Although our PbI\textsubscript{2} nanobelts have high quality, the device
fabrication processes can also degrade the performance of the
response speed. Further optimizations of device fabrication
process are needed in the future.

\section*{Conclusions}
In conclusion, large-scale synthesis of large-size PbI\textsubscript{2} nanobelts
are successfully accomplished by manipulating the source
materials mass, growth temperature, and growth time on
amorphous Si/SiO\textsubscript{2} substrate in a two-step vapor deposition

\textsuperscript{52-55} Please do not adjust margins


60. R. Saran and R. J. Curry, Nat. Photonics, 2016, 10, 81-92.