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# Synthesis, structure and photoelectric properties of selenide composites with in situ constructed $Sb_2Se_3$/$NaSbSe_2$ heterojunction

Donglou Ren[a], Zhuanghao Zheng[b], Meng Wei[a,b], Pengcheng Zhang[b], Michel Cathelinaud[a], Hongli Ma[a], Xianghua Zhang [a,*]

[a]ISCR (Institut des Sciences Chimiques de Rennes)-CNRS, UMR 6226, Univ. Rennes, F-35000, Rennes, France

[b]Shenzhen Key Laboratory of Advanced Thin Films and Applications, College of Physics and Optoelectronic engineering, Shenzhen University, Shenzhen, 518060, China

*Corresponding author: E-mail: xiang-hua.zhang@univ-rennes1.fr

Tel.: (+33) 02 23 23 69 37

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## Abstract

Inorganic semiconductor heterojunctions have attracted extensive attention for technological applications owing to interface phenomena. In this work, selenide composites with in situ constructed $Sb_2Se_3$/$NaSbSe_2$ heterojunctions with similar band gap width have been synthesized by conventional melt-quenching method. The microstructure and photoelectric properties of the composites were investigated at

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different $NaSbSe_2$ contents. The study revealed that $NaSbSe_2$ content has direct influences on the photoelectric performance of the composites by modifying the heterojunction size and the grain boundary resistance, as evidenced by scanning electron microscopy and impedance spectroscopy, respectively. The photocurrent density of $Sb_2Se_3$ with 2.5 and 5 mol% $NaSbSe_2$ was approximately 180 times larger than that of the pure $Sb_2Se_3$ at a bias voltage of -1.5 V and under an illumination of 7 $mW/cm^2$, due to an effective separation of photogenerated carriers through the interface electric field. Additionally, the composites exhibited an excellent stability even in 0.5 M $LiClO_4$ aqueous electrolyte.

***Key words:*** Selenide composites; Antimony selenide ($Sb_2Se_3$)-$NaSbSe_2$ heterojunction; Impedance spectroscopy; Photo-electro-chemical (PEC) performance; Interface electric field.

## 1. Introduction

In recent years, orthorhombic antimony selenide ($Sb_2Se_3$) is actively considered for different applications such as solar cells, photodetectors, photoelectrochemical cells, and thermoelectric devices [1-8]. This is because $Sb_2Se_3$ has some outstanding properties such as a narrow direct band gap (1.17 eV) [9], a high absorption coefficient ($> 10^5$ $cm^{-1}$) [10], a high Seebeck coefficient (1,800 $\mu VK^{-1}$) [5], and earth-abundant



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constituents [11]. However, application development of the $Sb_2Se_3$ based materials has been limited by its intrinsically high resistivity. One possibility to overcome this challenge is to dope this material with a low-valence metal cation [12-16]. The creation of internal heterojunctions seems to be an effective way to improve different photoelectric properties. For instance, Choi et al. [5] fabricated $Sb_2Se_3/Ag_2Se$ heterojunction nanowire that possessed a much better dark current and photocurrent, as compared to that of the intrinsic $Sb_2Se_3$ nanowire, to approximately 50 and 7 times, respectively. Guijarro et al. [17] constructed a $Sb_2Se_3/TiO_2$ heterojunction that exhibited a 3-fold improvement in the overall yield of the charge separated state upon illumination. In our previous work [18], internal $Sb_2Se_3/Cu_2GeSe_3$ heterojunction enhanced the photocurrent (74 $\mu A/cm^2$) that was at least 100 times higher than any of these two crystals individually ($Sb_2Se_3$: ~ 0.6 $\mu A/cm^2$, $Cu_2GeSe_3$: ~ 0.7 $\mu A/cm^2$). The enhanced photoelectric performance is attributed to the interface electric field that effectively promotes the separation and transport of photoinduced carriers.

Ternary semiconductors -the I-V-$VI_2$ family, where I = Cu, Ag, or alkali metals; V = Bi, Sb; and VI = S, Se, Te, have attracted increasing attention in thermoelectric [19-21] and solar cells [22-26]. Among these materials, ternary chalcogenide semiconductor $NaSbSe_2$ is another promising compound that is synthesized at high temperature with a NaCl-type structure and the lattice constant is 5.966(2) Å [27,28]. It has a narrow band gap of 1.1 eV [29] and a high absorption coefficient of $10^5$ $cm^{-1}$ at $\lambda$ = 600 nm [30]. If $Sb_2Se_3/NaSbSe_2$ heterojunction can be constructed, the influence of the interface between these two materials, with different structure but similar band gap,

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on the photoelectric performance will become very interesting. It is important to point out that the elements contained in the two materials are earth-abundant, low cost, nontoxic and environmentally friendly.

In the present work, the selenide composites with in situ synthesized $Sb_2Se_3$/$NaSbSe_2$ heterojunction have been prepared by using Sb, Se and Na elements as starting materials and by using the conventional melt-quenching method of vacuum-sealed silica tube to minimize the pollution. The influence of $NaSbSe_2$ contents on the heterojunction size and the photoelectric performance of the composites has been investigated. Ultimately, the possible mechanism of property enhancement is proposed.

## 2. Experimental procedure

*2.1. Materials preparation*

The selenide composites with internal $Sb_2Se_3$/$NaSbSe_2$ heterojunction were prepared by a conventional melt-quenching method. High-purity elements Sb shot (99.999%, 6 mm, Alfa Aesar), Se shot (99.999%), and Na ingot (99.95%) were used as raw materials. At first, all elements were weighted and mixed according to the appropriate stoichiometric ratio of each element (12 g mixture for each sample). The components are called SN-2.5%, SN-5%, SN-10% and SN-15%, S and N representing respectively $Sb_2Se_3$ and $NaSbSe_2$, and the number corresponding to the molar fraction of $NaSbSe_2$. The mixture was loaded into a carefully cleaned silica tube under protection of argon atmosphere in a glovebox. The tube has an inner diameter of 1 cm and an outer diameter 1.4 cm. Then, the tube containing all the starting elements was

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pumped to a vacuum of about $10^{-5}$ mbar. The flame-sealed tube was placed at the center of a rocking furnace. The mixture was then heated to 700 °C with a 1.2 °C/min ramp, rocked at this temperature for 8 h to ensure a good homogenization of the melt. The tube was subsequently quenched in water to room temperature. Finally, the ingots were annealed at 350 °C for 3 h, for reducing the mechanical stress caused during the quenching process. The as-synthesized samples were then removed from the silica tube, cut and polished into 2-mm-thick discs for subsequent characterizations.

*2.2. Characterization*

The phases in the as-synthesized samples were determined by X-ray diffraction (XRD) using a Bruker AXS D8 Advance X-ray diffractometer (Karlsruhe, Germany) coupled with Cu-$K_\alpha$ radiation ($\lambda$ = 1.5406 Å) in a scanning rate of 0.02° $s^{-1}$. The X-ray tube was operated at 40 mA and 40 kV in locked coupled mode. Scanning electron microscopy (SEM) studies were carried out on a JEOL JSM-7100F thermal field emission electron microscopy equipped with an energy dispersive X-ray spectroscopy (EDS) at 20 kV. The impedance spectroscopy and temperature-dependent conductivity were measured on an Autolab PGSTAT302N (Metrohm, AUT85901, Switzerland) in the temperature range of 278-373 K covering a frequency of $10^6$-1 Hz with two stainless-steel plates as electrodes and heating sample holder. All measured samples have a diameter of 10 mm and a thickness of 2 mm. To improve the contact between the electrodes and the sample, the surface of the samples was covered with a layer of Au. Spectra analyses were performed by Zsimpwin impedance analysis software. The

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photo-electro-chemical (PEC) performance of as-synthesized samples was evaluated using a three-electrode configuration, where Ag/AgCl electrode was used as the reference electrode, Pt-wire as the counter electrode and our samples as the working electrode. For obtaining the working electrode, the fine polished sample with diameter of 1 cm was connected with a copper wire by using silver paint as the back contact. Then, the sample was covered with a layer of epoxy resin for ensuring the isolation between electrode and electrolyte during the PEC measurement. The $LiClO_4$ solution (0.5 mol/L) was used as electrolyte and a white light tungsten halogen lamp was used as light source. The stability and the response speed of the photocurrent in our samples were evaluated under chopped light irradiation using a mechanical chopper. The optical property was measured with a step size of 1 nm using diffuse reflectance spectroscopy (DRS) equipped with an integrating sphere at room temperature. DRS experiments were carried out in the wavelength range of 300-2500 nm that covers the absorption zones, due to electronic transition of the semiconductor materials.

## 3. Results and discussion

### *3.1. Phase analysis and formation mechanism of composites*

Fig. 1 shows the XRD patterns of as-prepared selenide composites, obtained on polished bulk samples (Fig. 1(a)) or on grinded powders (Fig. 1(b)). The standard patterns corresponding to the orthorhombic $Sb_2Se_3$ (JCPDS# 15-0861) and cubic

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$NaSbSe_2$ (JCPDS# 77-2070) are included for reference. No other reaction products are detected in the XRD pattern of pure $Sb_2Se_3$. For the other samples (SN-2.5%, SN-5%, SN-10%, and SN-15%), the diffraction peaks are assigned to the orthorhombic $Sb_2Se_3$ and cubic $NaSbSe_2$ without other compound. For $NaSbSe_2$, the intensity of (200) and (220) peaks increases with increasing contents of $NaSbSe_2$. The XRD patterns of powders are similar to the XRD patterns of bulks, suggesting the samples prepared by melt-quenching method are homogeneous. This phenomenon was already observed in our previous works due to the mode of liquid mass transfer [31,32]. The grinding process destroyed the preferential orientation in the bulk samples, which caused some differences between the bulk and the powder in term of the relative intensity of peaks. These results suggest that the $Sb_2Se_3$-$NaSbSe_2$ composites were successfully prepared without impurity phase.

Because the materials were synthesized by melt-quenching method at 700 °C, the liquidus projection of the Na-Sb-Se system [27] (Fig. 2) is useful for understanding the formation mechanism. It can be seen that the largest primary crystallization field ($NaSbSe_2$) and the second-largest primary crystallization field ($Na_2Se$) are located in the ternary system. In addition, there is a big immiscibility area marked by dashed black line in the system. The system consists of eight binary compounds, $Na_3Sb$, NaSb, $Sb_2Se_3$, $Na_2Se_x$ (x = 1, 2, 3, 4, 6), and the only ternary compound $NaSbSe_2$. Although there exist many binary compounds in the Na-Sb-Se system, no one is detected by XRD in Fig. 1 except $Sb_2Se_3$. According to previous work [33], the $Na_2Se_6$, $Na_2Se_4$, $Na_2Se_3$, and $Na_2Se_2$ decomposed at 258 °C, 290 °C, 313 °C, and 435 °C, respectively. The low

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eutectic temperature of $Na_3Sb$ and NaSb is 437 °C [34]. These binary compounds may react with each other to generate $NaSbSe_2$. $Sb_2Se_3$ has a negative Gibbs free energy (-38.1152 kJ $mol^{-1}$) at 298 K [35,36] and a low melting point of 610 °C. The local atomic arrangement in liquid is similar to that of crystalline state [37]. Consequently, we have successfully prepared $Sb_2Se_3$-$NaSbSe_2$ composites after quenching, as evidenced by Fig. 1.

*3.2. Microstructural Characterization*

The backscattered electron images and energy dispersive X-ray spectroscopy are essential for studying the distribution of phases and elements. The images of the SN-2.5% and SN-15% samples are shown in Fig. 3(a,b). It clearly illustrates that several phases are distributed in the $Sb_2Se_3$ matrix with different sizes. To further determine the composition of these phases, the EDS was used to measure the composition of the points 1, 2 and 3 in Fig. 3(b), as shown as Table 1. It suggests that the point 1 is Se, point 2 is $NaSbSe_2$ and point 3 is $Sb_2Se_3$. It is observed that the Se is distributed around $NaSbSe_2$. The residual Se may be due to the imbalance of local compositions in liquid during melting or quenching process. According to a previous report [35], the liquidus Se and $Sb_2Se_3$ have a strong tendency toward immiscibility in some range of Se atomic percent. Moreover, there is a big immiscibility area [27] in Na-Sb-Se system (Fig. 2). The existence of Se in the composites has not been detected in XRD patterns (Fig. 1) due to the low content. The EDS elemental mappings of the SN-15% sample further proves that the distribution of elements is globally homogenous except few selenium

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rich domains (Fig. 3(c-e)). The distribution of Na element is quite uniform (Fig. 3(e)), because of the globally low content level, leading to high noisy background.

In order to observe the grain size of composites, the surface of the SN-15% sample was etched with a solution of 1 mol/L NaOH at ambient temperature. As shown in Fig. 4, it can be seen that the sample consists of $Sb_2Se_3$ (Na-doped, white) and $NaSbSe_2$ grains (gray) from the composition shown in Table 2 except the black holes. The average grain sizes of $Sb_2Se_3$ and $NaSbSe_2$ are approximately 50 μm and 5 μm, respectively. The EDS elemental mapping further reveals that the $NaSbSe_2$ has a homogeneous distribution in $Sb_2Se_3$. The formation mechanism of such microstructure can be explained as follows: in the liquidus, $NaSbSe_2$ and $Sb_2Se_3$ are phase separated due to their immiscibility observed in Fig. 2. A small amount of $NaSbSe_2$ phase precipitates firstly due to its higher melting point (740 °C) [27] and the crystals are randomly distributed in liquid $Sb_2Se_3$ which will crystallize afterwards. The same phenomenon was observed in SN-5% and SN-10% samples (not shown). These results indicate that the $Sb_2Se_3$/$NaSbSe_2$ heterojunctions were successfully in situ constructed by conventional melt-quenching method. It is generally observed that interface quality is often excellent when it is obtained by crystallization of liquid phases.

To further confirm the existence of heterojunctions inside the composites, the I-V curve of the SN-2.5% sample was characterized by using sputtered two gold contacts on the top and bottom surfaces (Fig. 5). The I-V curve displays a non-ohmic character, indicating that the SN-2.5% specimen contains internal heterojunctions, which is randomly distributed as shown in Fig. 3(a).

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*3.3. UV-vis diffuse reflectance spectroscopy*

The band gap of a semiconductor material is an important characteristic, which can be obtained by measuring the optical diffuse reflectance of the powders. The absorption spectra of all samples was converted from diffuse reflectance data by using the Kubelka-Munk and Tauc functions (Supporting Information). The band gap energy is then calculated by linear fit of the $(F(R)\cdot h\nu)^2 = B(h\nu - E_g)$ and the results are shown in Fig. 6 and Table 3 for all the samples. The band gap energy of pure $NaSbSe_2$ (1.21 eV) is higher than literature data (1.1 eV) [29], which is related to intrinsic defects obtained by different synthesis methods and conditions [38]. It can also be seen that the direct band gap of pure $Sb_2Se_3$ sample is 1.15 eV in agreement with previous work [10]. For the composites with internal $Sb_2Se_3/NaSbSe_2$ heterojunction, the direct band gaps are close to 1.17 eV. The narrow band gap energy would lead to a strong absorption of the solar spectrum.

*3.4. Impedance spectroscopy*

The electrical conductivity of different samples with a thickness of 2 mm and a diameter of 10 mm was measured by using impedance spectroscopy. Fig. 7 shows the variation of impedance real (Z′) part, impedance imaginary (Z″) part, and normalized Z″ with frequency at different temperatures for two representative samples SN-2.5% and SN-15%. It can be seen that the real part (Z′) of impedance decreases with increasing temperatures, corresponding to the behaviors of semiconductors [39].

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According to previous works [40,41], $Sb_2Se_3$ and $NaSbSe_2$ have a large number of intrinsic defects, such as $V_{Se}$, $V_{Na}$, $Na_{Sb}$, $Sb_{Se}$. The space charge effect is a dominant process at low temperatures and high frequencies, and in contrast, the space charge polarization is positive at low frequencies and high temperatures in term of $Z'$ [42]. The $Z'$ drastically reduces with increasing frequency, suggesting the space charge polarization [43] exists in these samples. The variation of imaginary part of impedance ($Z''$) with frequency at different temperatures, can be used to evaluate the relaxation frequency. It can be seen that the $Z''$ has a maximum peak with frequency at different temperatures (Fig. 7(b,e)). This peak in $Z''$ shifts towards high frequencies with increasing temperature and $NaSbSe_2$ content, which illustrates a decrease in the relaxation time and a thermally activated relaxation in the system [44]. A lower relaxation time implies faster movement of mobile charge carriers in the samples due to the existence of $Sb_2Se_3$/$NaSbSe_2$ heterojunction. The peak broadening at high temperatures, suggests that the temperature dependent relaxation process exists in theses materials [43]. The asymmetric broadening of peaks also illustrates the presence of electrical processes in the material with a spread of relaxation time as indicated by changes in peak width [45]. The relaxation may be caused by immobile species at low temperature and defects (vacancies, interstitials, and antisites) at higher temperature. The electrical conduction in the material is realized by hopping of electrons among the available localized sites [40,41,46,47]. The phenomenon was also observed in the normalized $Z''$ with frequency in Fig. 7(c, f). Moreover, the magnitude of $Z''$ declines with shifting peak frequency to high frequency direction with increase of $NaSbSe_2$

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content. This may be due to the accumulation of space charge in all materials in the high frequency zone. Similar result was also reported by other authors [46].

The Nyquist plots and the variation of conductivity with temperature were shown in Fig. 8. The asymmetric semicircular arcs appear in the impedance plot (Fig. 8(a,b)). The symmetry of semicircular arc depends on the nature of the material or its history [48]. The spectrum consists of single semicircular arc, which shrinks with increasing temperature. It further suggests that the all samples are semiconductors with a negative temperature coefficient of resistance. The bulk and grain boundaries effects exist in polycrystalline materials [49]. For selenide composites (SN-2.5% and SN-15%) with internal $Sb_2Se_3$/$NaSbSe_2$ heterojunctions, the plots include two semicircular arcs whose center is located below the real axis. The plots display the phenomena of semi-circle decentralization in the composites, which is frequently observed [50]. It can be seen that the electrical response is consisted of two overlapped semicircles. Due to the similar relaxation frequency, the high overlapping degree exists in the two semicircles. The first relaxation reflects the grains or bulk at high frequency and the second relaxation corresponds to the grain boundaries at low frequency. In our impedance spectra, the lack of electrode effect (line tail) in the range of experimental temperature indicates that all samples are electronic conductors, rather than ionic conductors.

According to the Debye's model, a material should be an ideal semicircle with the center on the real axis because of a single relaxation time [51]. However, the relaxation process is non-Debye type in our materials [52], due to the grain size, grain boundaries, grain orientation, defect distribution, etc [53]. In order to better understand the electrical

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response in materials, an equivalent circuit is necessary for fitting the measured data. The electrical properties are well illustrated by two parallel elements ($R_bC_b$-$R_{gb}C_{gb}$) and $R_0$ in series for these composites at 25 °C in Fig. 8(c), where $C_b$ = bulk capacitance; $C_{gb}$ = grain boundaries capacitance; $R_b$ = bulk resistance; and $R_{gb}$ = grain boundary resistance. The equivalent circuits of pure $Sb_2Se_3$ and $NaSbSe_2$ can be found in Fig. S4 (Supporting Information). $R_0$ corresponds to the high frequency intersection ($R_0$ = 0 for pure compounds), which is related to pores, capillary cavities, micro-cracks and even external contacts resistance [54-56]. It can be observed that these materials have a strong temperature dependence of conductivity (Fig. 8(d)). The curve was fitted by Arrhenius relation and activation energy for electrical conduction was obtained from the slope of the fitted lines. The equivalent circuit best fitted to measured data and the values of $R_0$, $R_b$, and $R_{gb}$, resistivity at 25 °C, and activation energy are shown in Table 4. The $NaSbSe_2$ has a bulk resistance of $8.63\times10^3$ Ω and a much higher grain boundary resistance of $1.44\times10^6$ Ω. However, the grain boundary resistance ($2.60 \times 10^5$ Ω) is close to the bulk resistance ($4.02 \times 10^5$ Ω) for $Sb_2Se_3$. This may relate to the crystalline structure of $Sb_2Se_3$ composed of intrinsic one dimensional $(Sb_4Se_6)_n$ ribbons with no dangling bonds at the edge, corresponding to grain boundaries [57]. However, $NaSbSe_2$ has a NaCl-type three-dimensional structure [58] that has an isotropic carrier transport and dangling bonds at grain boundaries. The dangling bonds typically act as recombination centers in three-dimensional crystal structure, such as Si, GaAs, CdTe, InP, and Cu(In,Ga)$Se_2$ (CIGS), which can be minimized by using different techniques including chemical surface/defect passivation and appropriate thermal processing [59-

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61]. Further, the concentration, the type and the distribution of defects in grain boundary and bulk/grain may be another reason for the difference in bulk and grain boundary resistance. The resistivity of $Sb_2Se_3$ and $NaSbSe_2$ is $2.14\times10^6$ Ω·cm and $8.87\times10^5$ Ω·cm, respectively. For the composites with internal $Sb_2Se_3$/$NaSbSe_2$ heterojunctions, the resistivity is reduced with increasing $NaSbSe_2$ contents, which is related to the interface defects. Similar work was also reported by O. Dier et al [62].

The activation energy, reflecting the energy for the hopping of electrons, of all $Sb_2Se_3$/$NaSbSe_2$ composites is between the quite similar values for pure $Sb_2Se_3$ and $NaSbSe_2$ (between 0.45 - 0.61 eV). It means that the activation energy is mainly governed by the hoping of electrons inside $Sb_2Se_3$ or $NaSbSe_2$. Therefore, the grain boundaries and the $Sb_2Se_3$/$NaSbSe_2$ interfaces are not difficult barriers for electrons to cross.

*3.5. Photo-electro-chemical (PEC) performance*

In order to explore the influence of heterojunction interface on the PEC performance of composites, the three-electrode configuration (Inset in Fig. 9) was used at ambient temperature. As shown in Fig. 9, all samples show cathodic photocurrents and their photocurrent density increases with increasing cathodic potential, indicating these materials are p-type semiconductors. The difference between dark and light current represents the photocurrent density. The photocurrent densities of pure $Sb_2Se_3$ and $NaSbSe_2$ are very weak (less than 1 μA/cm$^2$) (Fig. S5, Supporting Information), due to the absence of internal heterojunction that could effectively separate

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photogenerated carriers based on the interface electric field. Similar results can also be obtained in our previous works [16,18]. However, very important increase of photocurrent density has been observed in composites with internal heterojunctions. The values of photocurrent density (SN-2.5%: -139.87 μA/cm$^2$, SN-5%: -134.37 μA/cm$^2$, SN-10%: -44.26 μA/cm$^2$, and SN-15%: -72.47 μA/cm$^2$) at a bias voltage of -1.5 V are first reduced and then increased with increasing $NaSbSe_2$ contents. It can be explained as follows: Firstly, the internal heterojunctions could promote the separation of photogenerated electron-hole pairs, thanks to the interface electric field, and therefore prolong the carrier lifetime, resulting in higher photocurrent density when $NaSbSe_2$ content was low. The photocurrent densities of SN-2.5% and SN-5% samples are 139.87 μA/cm$^2$ and 134.37 μA/cm$^2$, respectively, which are approximately 180 times larger than that of pure $Sb_2Se_3$ (less than 1 μA/cm$^2$). Secondly, the number of $NaSbSe_2$/$NaSbSe_2$ grain boundaries increased with increasing $NaSbSe_2$ contents, resulting in fewer $Sb_2Se_3$/$NaSbSe_2$ interface. Meanwhile, the $NaSbSe_2$/$NaSbSe_2$ grain boundaries could cause higher recombination due to the three-dimensional structure and the dangling bonds at grain boundaries. This is illustrated by the recombination resistance [63] (grain boundary resistance) in Table 4. A larger recombination resistance suggests a lower rate of recombination [64]. The grain boundary resistance decreased with increasing $NaSbSe_2$ content for SN-10% sample, which caused the decreases of photocurrent density due to increased recombination of photogenerated carriers. Finally, the grain size of $NaSbSe_2$ is increased in SN-15% sample with increasing $NaSbSe_2$ content (Fig. 3), accompanied by increased area of $Sb_2Se_3$/$NaSbSe_2$ heterojunction

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interface. Compared with the reduced number of $Sb_2Se_3$/$NaSbSe_2$ interfaces, the increased area will become the dominant factor affecting the photocurrent density. Consequently, the photocurrent density of this sample is higher than that of SN-10% due to the effective separation of photogenerated carriers [65,66]. These results illustrate that the photoelectric properties of selenide composites are significantly enhanced through interface electric field of $Sb_2Se_3$/$NaSbSe_2$ heterojunction.

Furthermore, the cyclic photoresponse of the pure $Sb_2Se_3$ and selenide composites was characterized (Fig. 10(a)). When the light is turned on, the current densities quickly increase from -1.27 μA/cm$^2$ (dark) to -1.35 μA/cm$^2$ (light) for $Sb_2Se_3$ at a bias of -0.7 V. In contrast to $Sb_2Se_3$, the SN-5% sample has a much higher current density that increases from -4.56 μA/cm$^2$ (dark) to -10.93 μA/cm$^2$ (light) due to the interface electric field of heterojunction. Additionally, the current density drops once light is switched off. $Sb_2Se_3$ shows a sharp decrease with a recovery time ($\tau_{off}$) of 0.029 s, whereas all composites both show a slower decay such as SN-5% sample with $\tau_{off}$ of 0.076 s (Fig. S8, Supporting Information). This slow decay could be associated with the presence of charge trap centers and other defect states in composites, as already found in previous reports [67-69]. The photoresponse has not significant difference during at least 10 cycles, revealing the excellent stability of the selenide composites with internal heterojunctions. The speed of rise and fall for photocurrent is a good indicator of the photosensitivity for a material. Moreover, the photosensitivity ($S_{ph}$) of $Sb_2Se_3$ and composites was calculated by the following formula: $S_{ph} = (I_L - I_D)/I_D = (J_{ph} - J_d)/J_d$ [67], where $I_L$, $I_D$, $J_{ph}$, and $J_d$ represent illuminated current, dark current, photocurrent density,

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and dark current density, respectively. The $S_{ph}$ values are 0.049, 1.638, 2.102, 2.000, and 1.870 for pure $Sb_2Se_3$, SN-2.5%, SN-5%, SN-10%, and SN-15% samples, respectively. It is obvious that the $S_{ph}$ value of pure $Sb_2Se_3$ is much lower than that of the composites. It further proved that the composites with internal heterojunctions have much better photosensitivity, resulting in the higher photocurrent density (approximately 180 times) as compared to $Sb_2Se_3$.

Fig. 10(b) displays the relationship between the incident light intensity and the current density at a bias voltage of -0.7 V. The relation can be expressed as $J_{ph} \propto P^{\theta}$, where $J_{ph}$ is the photocurrent density, P is the power density of the incident light, and θ is an exponent [16]. The θ value was obtained by linear fitting in the form of double log-plot. All θ values are smaller than that of low trap state (θ = 1), which can be attributed to the complex process of carriers generation, trapping and recombination in composites [70].

*3.6. Mechanism of the enhanced PEC performance*

On the basis of the above results, the possible mechanism of the enhanced PEC performance of composites is proposed (Fig. 11). The valence band (VB) and the conduction band (CB) potential of $Sb_2Se_3$ and $NaSbSe_2$ can be calculated by the following empirical formulae [71,72]: $E_{VB} = X - E^e + 0.5\ E_g$ and $E_{CB} = E_{VB} - E_g$, where $E_{VB}$ is the VB edge potential, $E_{CB}$ is the CB edge potential, $E_g$ is the band gap energy of the semiconductor, $X$ is the electronegativity of the semiconductor, and the values of $Sb_2Se_3$ and $NaSbSe_2$ were calculated according to the electronegativity of the constitute

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atoms [73]. $E^e$ is the energy of free electrons on the hydrogen scale (~ 4.5 eV). As a result, the X values for $Sb_2Se_3$ and $NaSbSe_2$ are 5.41 eV and 4.66 eV, respectively. The VB and CB of $Sb_2Se_3$ were separately calculated to be 1.48 eV and 0.34 eV. Similarly, the VB and CB of $NaSbSe_2$ correspond to 0.76 eV and -0.44 eV, respectively. The Fermi level of $NaSbSe_2$ is pinned at 0.45 eV above VB from the early report [40]. The Fermi level in $Sb_2Se_3$ laid in the middle of CB and VB [74] that located at 0.91 eV, which helps us to draw the band diagram. When $Sb_2Se_3$ and $NaSbSe_2$ contact with each other, the heterojunction interface is formed with an electric field. Both of $Sb_2Se_3$ and $NaSbSe_2$ can be easily excited and produce electron-hole pairs under visible light illumination due to their narrow direct band gaps. The photoinduced electrons could more easily transfer from the CB bottom of $NaSbSe_2$ to that of $Sb_2Se_3$ under the effect of interface electric field, while the holes left on the VB top of $Sb_2Se_3$ moved in the opposite direction to VB top of $NaSbSe_2$. Therefore, the heterojunction interface, not only improves the separation efficiency of the photogenerated electrons and holes, but also prolong the lifetime of photoinduced carriers, leading to higher photocurrent density.

## 4. Conclusion

Selenide composites with in situ synthesized $Sb_2Se_3$/$NaSbSe_2$ heterojunctions based on two materials having close band gap energy were successfully prepared via the reaction among Sb, Se and Na by using conventional melt-quenching method, which is favourable for forming a high-quality solid-solid interface without pollution.

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The impedance spectroscopy shows that the composites are electronic conductors and the photo-electro-chemical measurement reveals that the composites have a p-type conducting characteristics. The photocurrent density of composites is firstly reduced and then increased with increasing $NaSbSe_2$ contents, which is related to the decreased grain boundary resistance and increased heterojunction size. The interface electric field of the $Sb_2Se_3/NaSbSe_2$ heterojunctions helped effectively the separation of the photogenerated electron-hole pairs. The photocurrent density of $Sb_2Se_3$ with 2.5 and 5 mol% $NaSbSe_2$ contents was approximately 180 times larger than that of the pure $Sb_2Se_3$ at a bias voltage of -1.5 V and under an illumination of 7 $mW/cm^2$. Additionally, the composites exhibited an excellent stability even in 0.5 M $LiClO_4$ aqueous electrolyte. Considering the enhanced photocurrent density and the excellent stability, the selenide composite with internal $Sb_2Se_3/NaSbSe_2$ heterojunctions can be considered as a promising candidate for PEC water splitting and photocatalysis.

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

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## Figure captions

**Fig. 1.** XRD patterns taken from the pure $Sb_2Se_3$, SN-2.5%, SN-5%, SN-10% and SN-15% samples: (a) bulks and (b) powders.

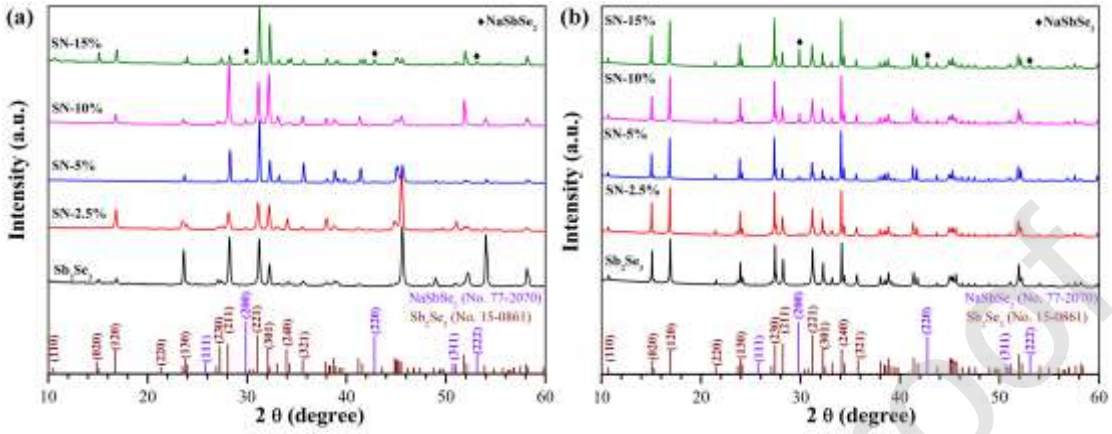



**Fig. 2.** The liquids projection of Na-Sb-Se system [27].

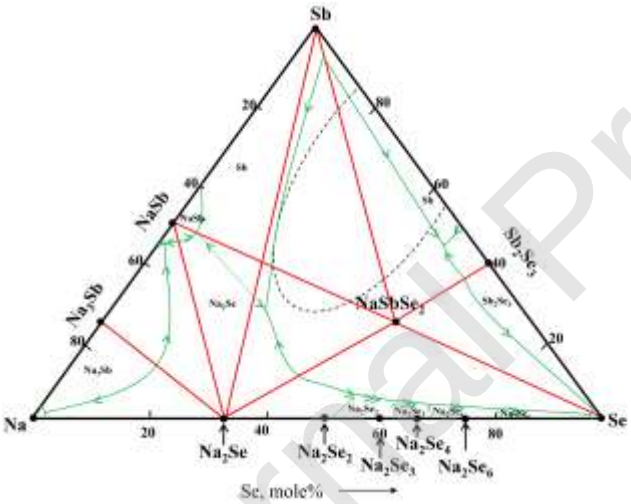



**Fig. 3.** Backscattered electron images of (a) SN-2.5% and (b) SN-15%. (c-e) the X-ray elemental mappings for Sb, Se, and Na in (b), respectively.

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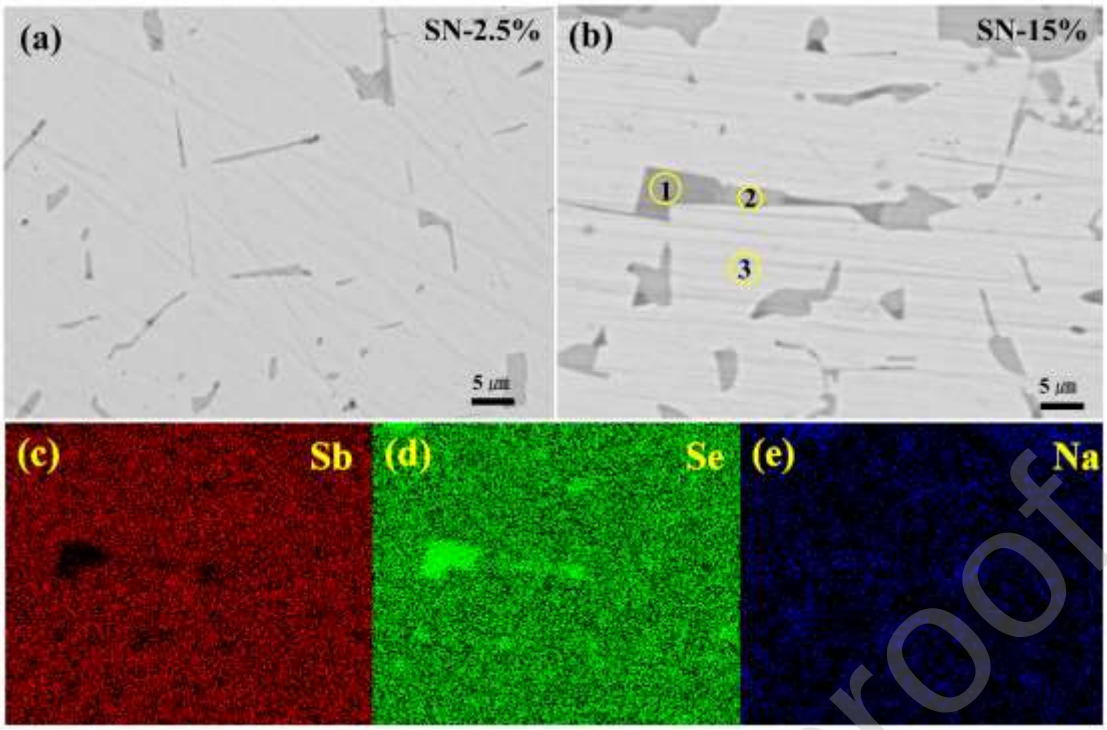



**Fig. 4.** Backscattered electron micrograph of etched surface of SN-15% sample and the X-ray elemental mappings for Sb, Se, and Na, respectively.

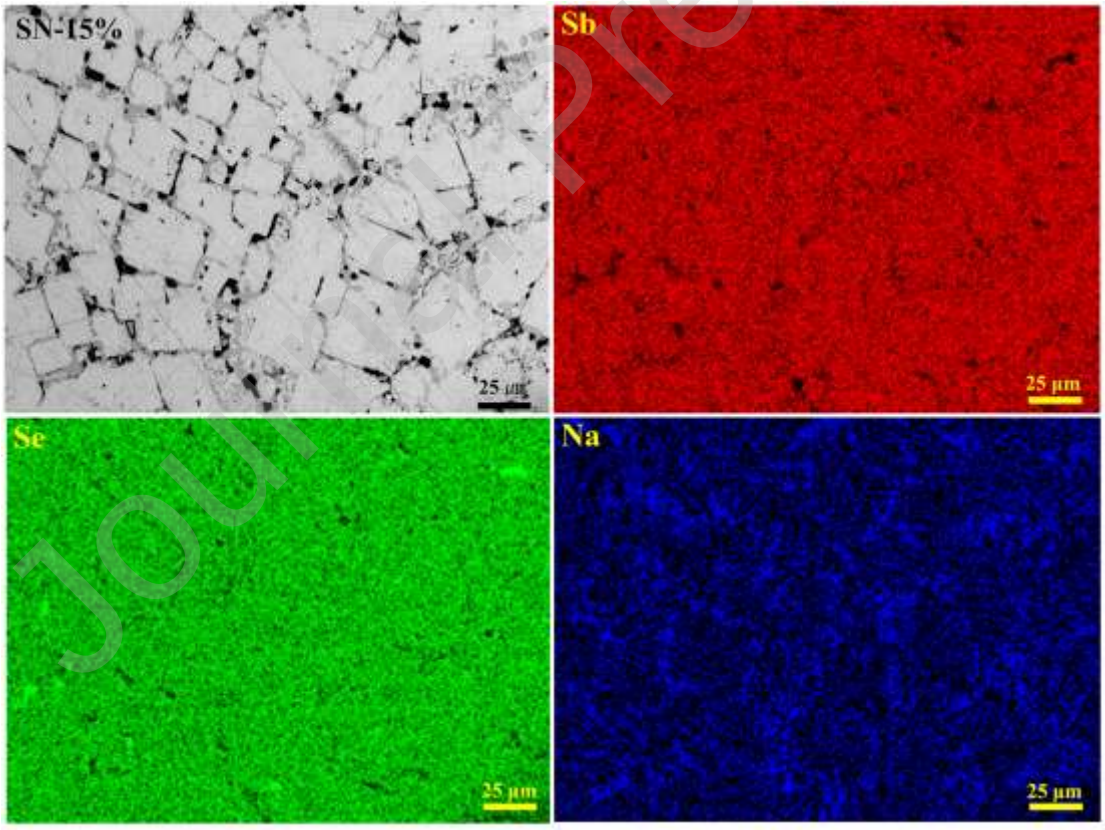



**Fig. 5.** The I-V curve of SN-2.5% sample in the voltage range of -0.8 to 0.8 V. Inset is

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the schematic illustration of the sample during measurement process.

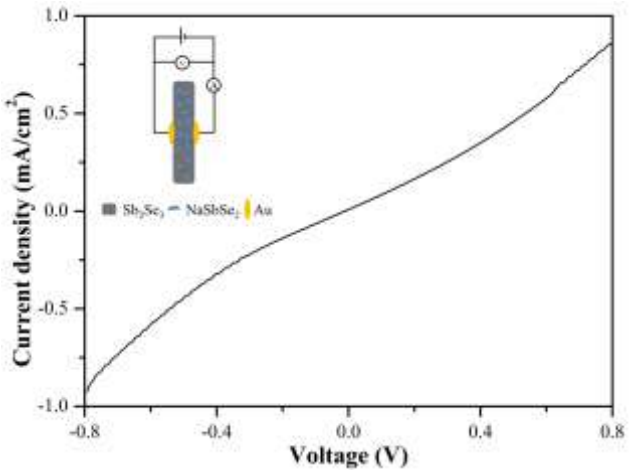



**Fig. 6.** Tauc plot of pure $Sb_2Se_3$, $NaSbSe_2$, SN-2.5%, SN-5%, SN-10% and SN-15% samples.

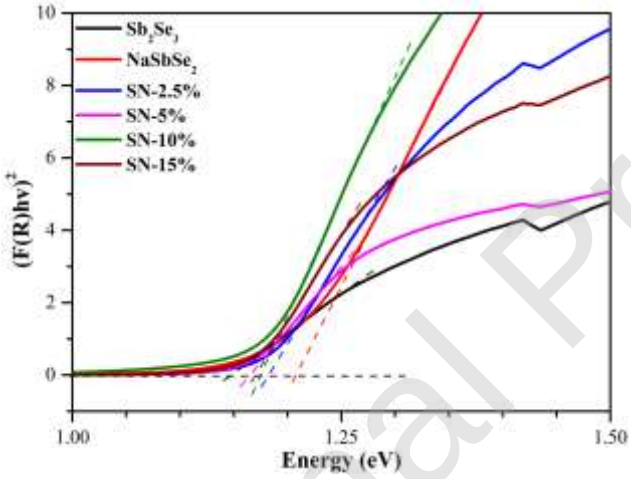



**Fig. 7.** The frequency dependence of impedance real (Z′) part, impedance imaginary (Z″) part, and normalized Z″ at different temperatures: (a-c) SN-2.5%; (d-f) SN-15%.

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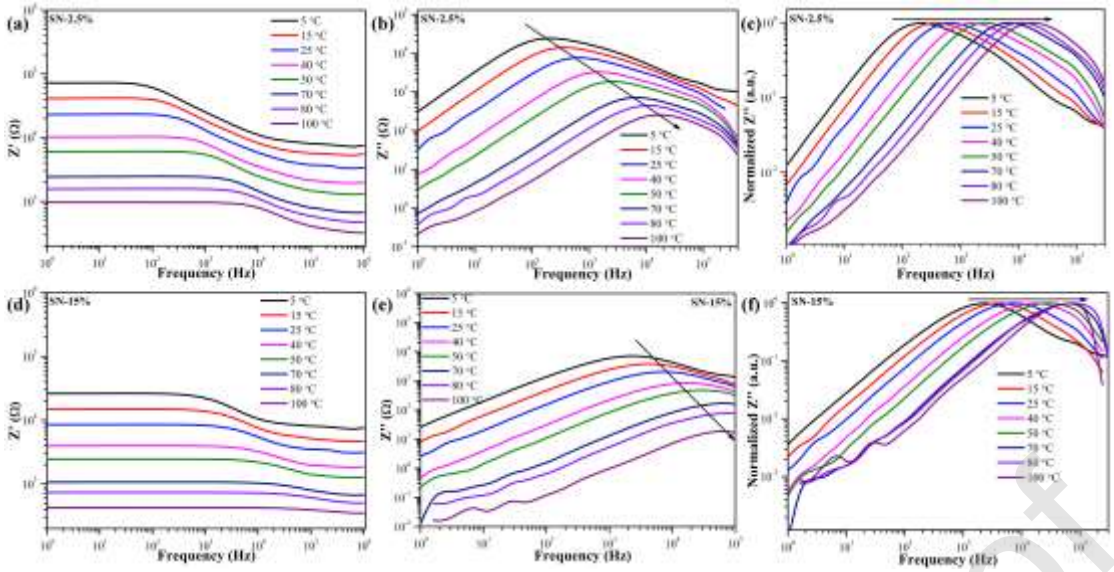



**Fig. 8.** Complex impedance plots of Z' versus Z″ (Nyquist plot) at different temperatures: (a) SN-2.5%; (b) SN-15%. (c) Complex impedance spectrum of composites with electrical equivalent circuit (inset) at 25 °C. (d) Conductivity of composites as a function of temperature.

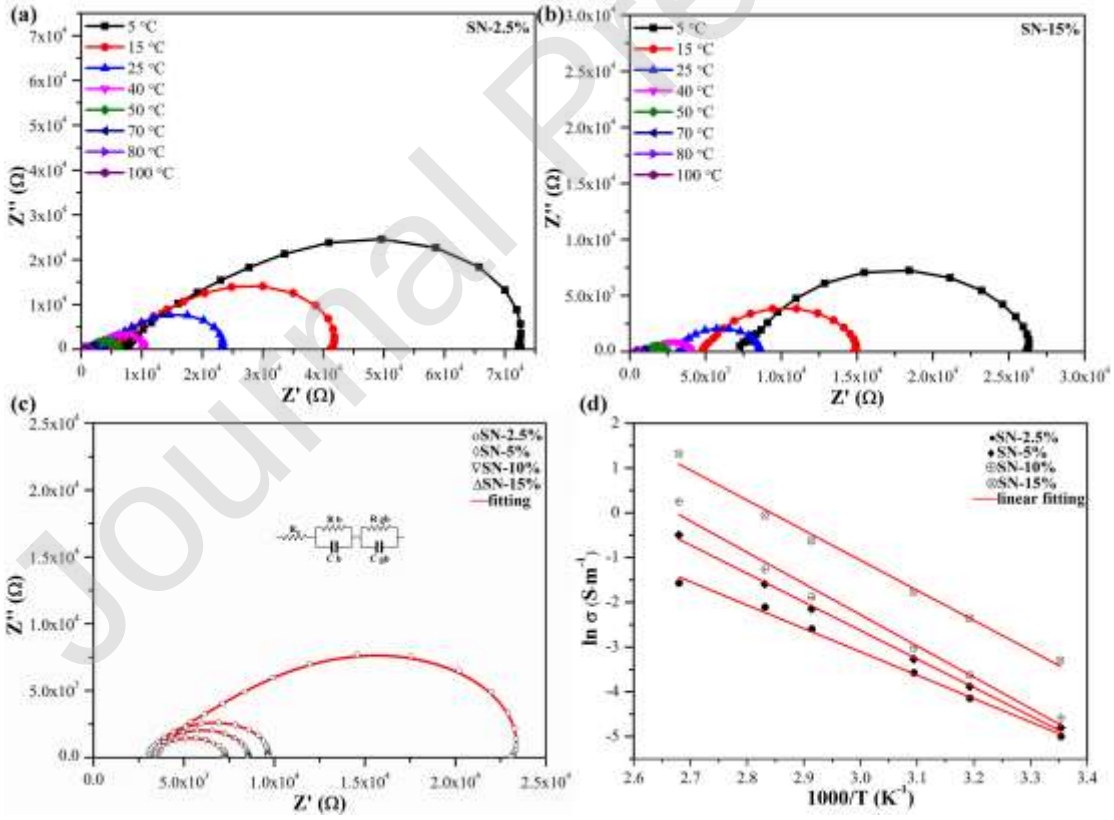



**Fig. 9.** Photoelectrochemical response of pure $Sb_2Se_3$, SN-2.5%, SN-5%, SN-10% and

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SN-15% samples illuminated with a chopped light power density of 7 mW/cm$^2$. Inset is the schematic diagram of the three-electrode configuration.

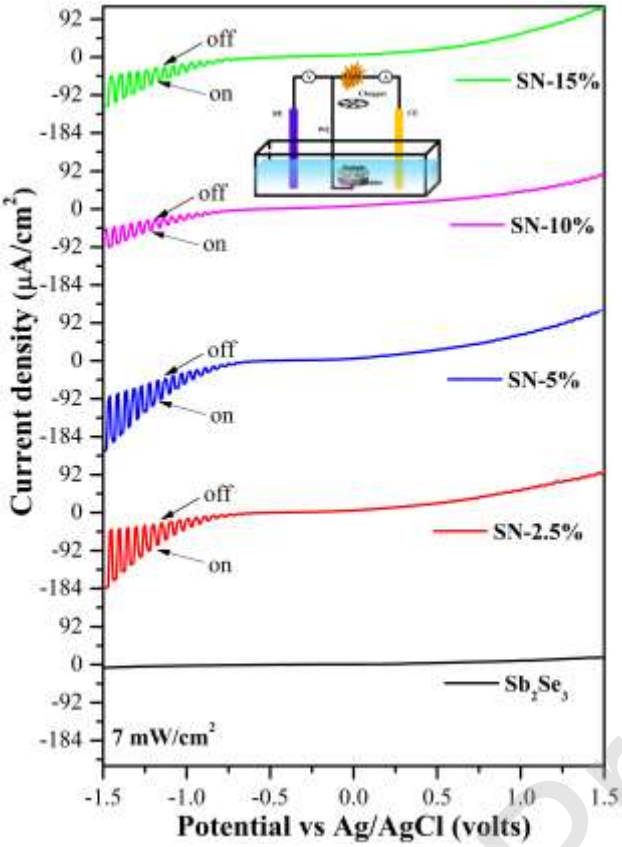



**Fig. 10.** (a) Time-resolved PEC photoresponse of pure $Sb_2Se_3$ and composites at light power density of 17.6 mW/cm$^2$ at -0.7 V. (b) The incident light intensity dependence of current density at a bias voltage of -0.7 V.

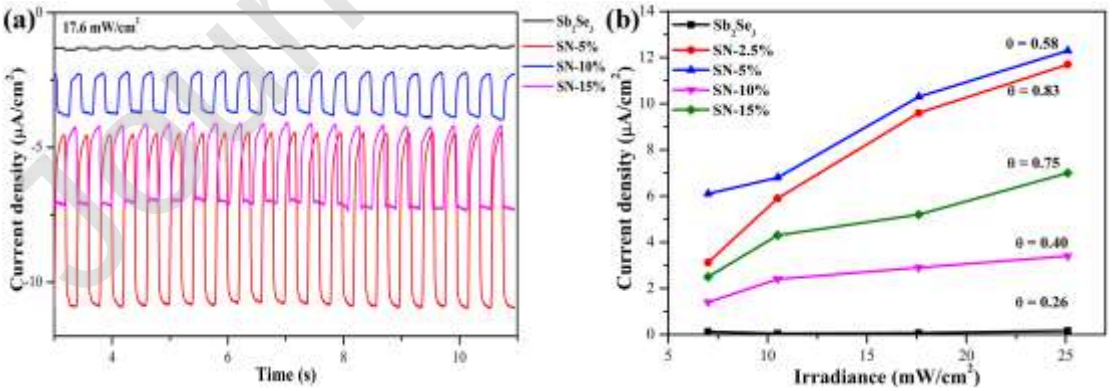
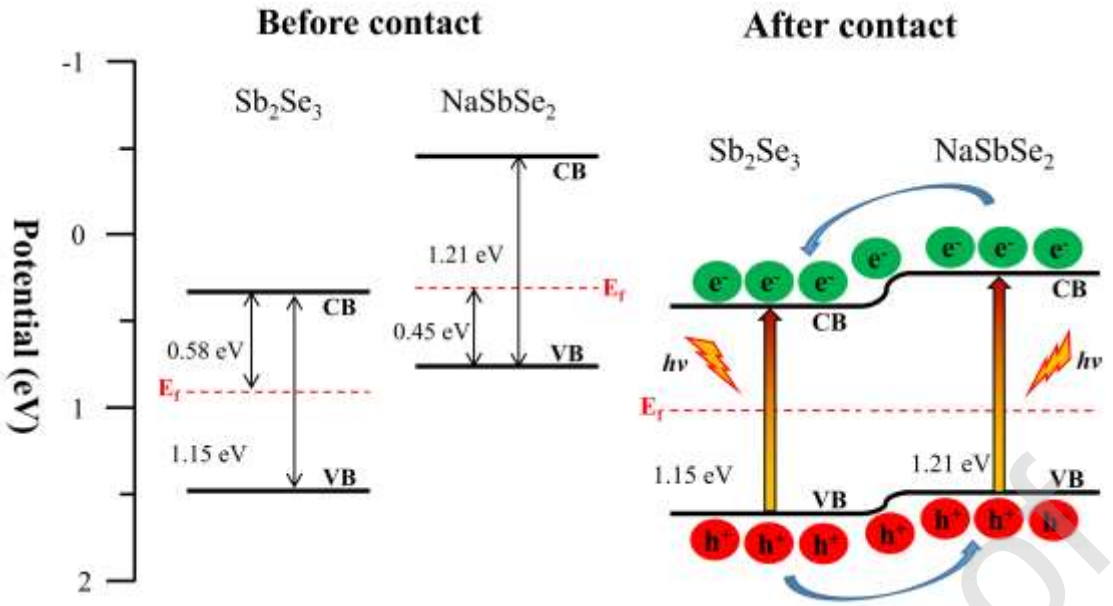



**Fig. 11.** Schematic illustration for the separation and transfer of photogenerated charges in the region of the interface between the $Sb_2Se_3$ and the $NaSbSe_2$.




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**Table captions**

**Table 1.** The compositions of points 1, 2 and 3 in SN-15% sample.

| Point | Composition (at.%) | | |
|---|---|---|---|
| | Na | Sb | Se |
| 1 | 0 | 2.48 | 97.52 |
| 2 | 24.6 | 25.3 | 50.1 |
| 3 | 0.22 | 39.34 | 60.44 |

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**Table 2.** After NaOH (1 M) etching, the compositions of white and gray areas in SN-15% sample.

| Area | Composition (at.%) | | |
|---|---|---|---|
| | Na | Sb | Se |
| white | 0.55 | 39.34 | 60.11 |
| gray | 15.01 | 29.94 | 55.05 |

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**Table 3.** The energy gap values of all compounds.

| Sample | $Sb_2Se_3$ | $NaSbSe_2$ | SN-2.5% | SN-5% | SN-10% | SN-15% |
|---|---|---|---|---|---|---|
| Energy gap (eV) | 1.15 | 1.21 | 1.18 | 1.16 | 1.17 | 1.17 |

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**Table 4.** Values of $R_{gb}$, $R_b$, $R_0$, resistivity at 25 °C, and activation energy of $Sb_2Se_3$, $NaSbSe_2$, and composites.

| Sample | $R_{gb}$ (Ω) | $R_b$ (Ω) | $R_0$ (Ω) | Resistivity (Ω·cm) | Activation energy (eV) |
|---|---|---|---|---|---|
| $Sb_2Se_3$ | $2.60\times10^5$ | $4.02\times10^5$ | — | $2.14\times10^6$ | 0.61 |
| $NaSbSe_2$ | $1.44\times10^6$ | $8.63\times10^3$ | — | $8.87\times10^5$ | 0.45 |
| SN-2.5% | $1.55\times10^4$ | $4.07\times10^3$ | $3.70\times10^3$ | $1.48\times10^4$ | 0.45 |
| SN-5% | $4.66\times10^3$ | $1.85\times10^3$ | $3.14\times10^3$ | $1.20\times10^4$ | 0.55 |
| SN-10% | $2.36\times10^3$ | $1.55\times10^3$ | $3.35\times10^3$ | $9.71\times10^3$ | 0.60 |
| SN-15% | $3.09\times10^3$ | $2.08\times10^3$ | $3.39\times10^3$ | $2.67\times10^3$ | 0.58 |

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