Enhanced Low-Temperature Thermoelectric Performance in (PbSe)$_{1+\delta}$(VSe$_2$)$_1$ Heterostructures due to Highly Correlated Electrons in Charge Density Waves

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ABSTRACT: We explore the effect of charge density wave (CDW) on the in-plane thermoelectric transport properties of (PbSe)$_{1+\delta}$(VSe$_2$)$_1$ and (PbSe)$_{1+\delta}$(VSe$_2$)$_2$ heterostructures. In (PbSe)$_{1+\delta}$(VSe$_2$)$_1$ we observe an abrupt 86% increase in the Seebeck coefficient, 245% increase in the power factor, and a slight decrease in resistivity over the CDW transition. This behavior is not observed in (PbSe)$_{1+\delta}$(VSe$_2$)$_2$ and is rather unusual compared to the general trend observed in other materials. The abrupt transition causes a deviation from the Mott relationship through correlated electron states. Raman spectra of the (PbSe)$_{1+\delta}$(VSe$_2$)$_1$ material show the emergence of additional peaks below the CDW transition temperature associated with VSe$_2$ material. Temperature-dependent in-plane X-ray diffraction (XRD) spectra show a change in the in-plane thermal expansion of VSe$_2$ in (PbSe)$_{1+\delta}$(VSe$_2$)$_1$ due to lattice distortion. The increase in the power factor and decrease in the resistivity due to CDW suggest a potential mechanism for enhancing the thermoelectric performance at the low temperature region.

KEYWORDS: Charge density wave, transition-metal dichalcogenide, thermoelectrics, thermoelectricity, energy conversion, many body

INTRODUCTION

Since the 1950s, many researchers have tried to improve the thermoelectric efficiency of materials using various strategies including asymmetric density of states in low dimensional materials,\textsuperscript{1,2} engineering materials and nanostructures with low lattice thermal conductivity,\textsuperscript{3,4} and distortion of the density of states and creating resonant levels in the materials.\textsuperscript{5,6} It should be noted that, while there are relatively good thermoelectric materials (i.e., ZT $\sim$ 1) at room temperature and elevated temperatures (e.g., 800–1000 °C), there are currently no efficient thermoelectric materials at low temperatures. The phenomenon presented here can potentially provide a new mechanism for increased thermoelectric performance at low temperatures that deviates from the standard Mott relationship through the creation of correlated electron states. Several transition-metal dichalcogenides (TMDCs) exhibit charge density wave (CDW) transitions at low temperatures.\textsuperscript{7,8} Below the transition temperature, $T_{CDW}$, the atomic lattice forms a periodic structural distortion, which creates a condensed ground state of electrons and a gap in the Fermi surface.\textsuperscript{7,8} As a result, the electrical resistivity usually increases below $T_{CDW}$. Under applied electrostatic gate fields, the CDW can become unpinned from impurities and slide with respect to the lattice. The sliding CDW can then contribute to the electron transport, adding to the single-particle conductance contribution.\textsuperscript{9,10} This collective conductance caused by the CDW sliding motion can be modulated with an applied gate voltage up to 2 orders of magnitude higher than the single-particle conductance.\textsuperscript{11}

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In TiSe₂ and VSe₂, the resistivity increases due to the CDW transition and the transition temperature has been found to depend on both the applied pressure and layer thickness,¹²⁻¹⁵ which tune the interlayer interaction. VSe₂ is composed of hexagonally stacked Se—V—Se sheets with interlayer van der Waals bonding¹⁴ and has a CDW transition temperature near 100 K.¹⁶ Recent work by the Johnson group has shown that the transition temperature can be tuned by changing the PbSe separation thickness (n) or the VSe₂ layer thickness (m) in [(PbSe)₁₉₈₋₈₄(VSe₂)₈₄] heterostructures.¹⁷,¹⁸ The in-plane resistivity increase below T_{CDW} is found to be most pronounced in [(PbSe)₁₉₈₋₈₄(VSe₂)₁₈₄] structures. The in-plane resistivity increases below T_{CDW} in [(PbSe)₁₉₈₋₈₄(VSe₂)₁] structures are much more pronounced than observed in bulk VSe₂.¹⁷,¹⁸ To our knowledge, no thermoelectric measurements have been performed on this interesting new materials system. The cross-plane thermal conductivity of semiconducting layered heterostructures has been found to be ultralow (κ ∼ 0.05 W/m-K), making them promising candidates for thermoelectric applications.³ The in-plane lattice thermal conductivity of these materials has also been found to be quite low (κ ≈ 0.4 W/m-K) according to the measurements with the use of suspended microdevices.¹⁹,²⁰ Both the in-plane and cross-plane thermal conductivity measurements were done on semiconducting systems, where the electronic contribution to the thermal conductivity (κ_e) is negligible. In comparison, κ_e can be significant in [(PbSe)₁₉₈₋₈₄(VSe₂)₈₄] in the normal metallic state above T_{CDW} and can be calculated from the measured electrical conductivity using the Wiedemann—Franz law.²¹,²² However, the Wiedemann—Franz law does not necessarily hold true for CDW systems²³ due to electron—electron interactions as well as the collective conductance associated with the sliding motion of the CDW from electron—phonon coupling.²⁴⁻²⁸ Previous thermal conductivity measurements across the CDW transition have shown an unusual peak in thermal conductivity at the CDW transition, which was explained by an additional contribution from low frequency phasons.²⁹,³⁰

Here, we explore the thermoelectric transport properties of (PbSe)₁₉₈₋₈₄(VSe₂)₁ and (PbSe)₁₉₈₋₈₄(VSe₂)₂ heterostructures both above and below the charge density wave transition temperature observed in the (PbSe)₁₉₈₋₈₄(VSe₂)₁ heterostructure. These measurements entail both in-plane electrical conductivity and Seebeck coefficient measurements as a function of temperature. We also measure the temperature dependence of the lattice parameters of (PbSe)₁₉₈₋₈₄(VSe₂)₁ and determined from the diffraction patterns.

**RESULTS AND DISCUSSION**

Figure 1 shows optical microscope images of the sample used to measure the in-plane Seebeck coefficient and electrical resistivity, via a 4-point resistivity measurement which eliminates the effect of contact resistance. Here, the Seebeck coefficient was measured by small microfabricated heaters and thermometers fabricated using electron beam lithography. The [(PbSe)₁₉₈₋₈₄(VSe₂)₈₄] films, approximately 50 nm thick, were deposited in lithographically defined windows approximately 50 μm × 50 μm in size followed by a lift-off process.²⁹,³¹ We measured the temperature dependence of the Raman spectra in an optical cryostat. The [(PbSe)₁₉₈₋₈₄(VSe₂)₈₄] films used in this study were formed via the self-assembly of various precursors by physical vapor deposition (PVD) of elemental sources in a home-built high vacuum chamber (<5 × 10⁻⁷ Torr). Pb and V were deposited by electron beam evaporation, and Se was deposited with a Knudsen effusion cell. Each constituent element was deposited sequentially to form the layered precursors that matched the chemical component ratios of each desired target structure. The distance between the source and substrates was approximately 1 m, and evaporation rates were maintained below 1 Å/s. Films were deposited on both unpatterned substrates (for structural characterization) and patterned substrates (for in-plane transport measurements). Calibrated deposition parameters have been previously reported for the [(PbSe)₁₉₈₋₈₄(VSe₂)₈₄] compounds.³² The films were crystallized into the layered structures after the deposition in an inert N₂ environment by heating to 250 °C for 60 min.

![Figure 1. Optical microscope image of in-plane (a) Seebeck and (b) resistivity measurements of the (PbSe)₁₉₈₋₈₄(VSe₂)₁ films. (c) HAADF-STEM image of the (PbSe)₁₉₈₋₈₄(VSe₂)₁ heterostructure film.](image-url)
The thickness of as-deposited films was 50 nm. Figure 1c shows the high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) measurement of the \((\text{PbSe})_{1}\delta(\text{VSe}_2)_n\) heterostructure film. In the figure, alternating PbSe and VSe$_2$ layers are clearly distinct from each other. Here, the PbSe layers are considerably brighter than the VSe$_2$ layers.

X-ray diffraction characterization of the \((\text{PbSe})_{1}\delta(\text{VSe}_2)_n\) heterostructures was performed after annealing the precursors. Figure 2 contains the X-ray reflectivity of two samples investigated in this work. The spectra contain Kiessig fringes beyond 10° indicates that the films have less than an angstrom of roughness within the coherence of the X-ray source. All of the maxima in the specular diffraction patterns can be indexed as 00l planes, indicating that the samples are crystallographically aligned with the substrate. The c-axis lattice parameters calculated from the patterns \((c = 12.23(1) \text{ Å} \text{ and } 18.31(1) \text{ Å})\) for \((\text{PbSe})_{1}\delta(\text{VSe}_2)_1\) and \((\text{PbSe})_{1}\delta(\text{VSe}_2)_2\), respectively) agree with those previously reported. The maxima in the grazing incident in-plane diffraction patterns can all be indexed as \(hk0\) reflections of either PbSe or VSe$_2$ planes, confirming the crystallographic alignment of the crystals with the substrate. The in-plane lattice parameters are consistent with those previously reported. The lengths of the a-axis of PbSe are 6.06(1) Å for both materials, and the a-axis lengths of VSe$_2$ are 3.43(1) Å and 3.40(1) Å for \((\text{PbSe})_{1}\delta(\text{VSe}_2)_1\) and \((\text{PbSe})_{1}\delta(\text{VSe}_2)_2\), respectively. Figure 2c shows that the PbSe pattern contains 110 and 310 reflections that are forbidden in the rock salt structure, indicating that the crystal structure, while still cubic, has distorted slightly from that of the bulk. Lattice parameters were determined from in-plane X-ray diffraction (XRD) spectra of the \((\text{PbSe})_{1}\delta(\text{VSe}_2)_1\) compound collected as a function of temperature at the Advanced Photon Source (APS) and are plotted as a function of temperature in Figure S1 of the Supporting Information. The slope of the change in the in-plane lattice parameter as a function of temperature of VSe$_2$ changes its sign at ~125 K, indicating that VSe$_2$ layers undergo a structural transition at low temperature while the PbSe does not.

Figure 3 shows a comparison of the in-plane electrical resistivity and Seebeck coefficient plotted as a function of temperature over the range of 77−300 K for both the \((\text{PbSe})_{1}\delta(\text{VSe}_2)_1\) and \((\text{PbSe})_{1}\delta(\text{VSe}_2)_2\) heterostructures. For the \((\text{PbSe})_{1}\delta(\text{VSe}_2)_1\) material, the electrical resistivity shows a minimum around \(T = 140 \text{ K}\), while the \((\text{PbSe})_{1}\delta(\text{VSe}_2)_2\) material shows a linear monotonically increasing resistivity with temperature over the entire temperature range as expected for a metal. These results are consistent with our previous measurement of charge density waves in this material system, where we reported a CDW transition around 140 K for the 1:1 material and not the 1:2 material. The Seebeck coefficient plotted in Figure 3b shows a large abrupt increase from 10.6 to 19.7 \(\mu\text{V/K}\) (increases by 85%) for the \((\text{PbSe})_{1}\delta(\text{VSe}_2)_1\) film when the temperature is lowered from 150 to 136 K, while the resistivity actually decreases from 3.768 to 3.765 \(\mu\text{Ohm}\cdot\text{m}\) over the same temperature range (shown in the inset in Figure 3a). \((\text{PbSe})_{1}\delta(\text{VSe}_2)_2\) does not show this behavior and has a relatively low Seebeck coefficient (3.4 \(\mu\text{V/K}\)). Tani et al. reported a similar abrupt change in the Seebeck coefficient of IT-TaS$_2$ around 210 K due to a CDW transition. However, this behavior was observed only in one out of a total of six samples. Bhatt et al. and Huang et al. reported Seebeck coefficient measurements through the CDW transition of TiSe$_{2-\delta}$, which resulted in gradual changes in the resistivity and Seebeck coefficient. However, the suppression of the CDW transition actually improved the thermoelectric performance in their samples. Naik and Rastogi studied 2H-NbSe$_2$ with and without Ga-intercalation and found that resistivity shows a kink and the Seebeck coefficient has broad maximum around 35 K for a single crystalline structure and that the CDW effect is quenched with Ga-intercalation. Compared to a previous thermoelectric study on other CDW materials, the enhancement in the Seebeck coefficient and the power factor observed in our \((\text{PbSe})_{1}\delta(\text{VSe}_2)_1\) heterostructures results from two reasons. The first reason is that reducing...
the dimensions of the VSe\textsubscript{2} component to the monolayer limit will enhance the CDW order and Fermi-surface nesting through correlated electron states.\textsuperscript{26–28} Research by Feng et al. shows that their density functional theory (DFT) calculation overestimates the bandwidth of near-\(E_F\) energy states compared to experimentally observed values by a factor of 1.4. The discrepancy is attributed to electron–electron interaction from V 3d orbitals that has not been included in the DFT.\textsuperscript{26} Duvjir et al. demonstrate strong CDW order and perfect Fermi-surface nesting due to enhanced electron–electron correlations in monolayer VSe\textsubscript{2}.\textsuperscript{27,28} Second, the heterointerface between the VSe\textsubscript{2} and PbSe layers also plays an important role in electronic reconstruction.\textsuperscript{27} A metal–insulator transition was observed around 135 K in a monolayer VSe\textsubscript{2}/bilayer graphene system, which is caused by hetero-interfacial coupling between VSe\textsubscript{2} and graphene layers, such as interlayer charge transfer and hybridization.\textsuperscript{27} We observe only enhanced thermoelectric performance in (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{1}, because the CDW is observed only when there is a monolayer VSe\textsubscript{2} sandwiched by two PbSe layers. In the (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{2} heterostructure the CDW is similar to that observed in bulk VSe\textsubscript{2}. Above the CDW transition temperature, the two materials (1:1 and 1:2 heterostructures) studied here show very similar behaviors with the VSe\textsubscript{2} in the metallic state. We observed the same Seebeck and resistivity temperature-dependent profiles on several different samples. In order to characterize the thermoelectric performance of those materials, power factors as a function of temperature have been calculated and are shown in Figure 3c. The power factor of the (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{1} film changes from 29.8 \(\mu W/m/K\) above to 102.9 \(\mu W/m/K\) below the CDW transition, corresponding to a 245\% increase in the power factor. This large enhancement in the power factor of the (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{1} film originates from a sudden jump in the Seebeck coefficient and slight decrease in resistivity. The power factor of (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{1} is 4.4 \(\mu W/m/K\) at the transition temperature. The ratio of power factors between these two materials increases from 7 above to more than 23 below the CDW. At 80 K the ratio of the power factors has increased to 90 [the (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{1} film has a power factor 0.8 \(\mu W/m/K\), while (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{1} has a power factor of 72 \(\mu W/m/K\)]. We would like to emphasize that the 1:2 heterostructures (i.e., (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{2}) did not show a CDW transition, and we believe this phenomenon is unique to the monolayer structure. Hite et al. found that the temperature-dependent mobility of the (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{1} heterostructure decreases from 1.1 to 0.6 \(cm^2/V\cdot s\) when the temperature decreases from 300 to 120 K. When the temperature is below the CDW transition temperature, the mobility starts to increase and reaches 1.6 \(cm^2/V\cdot s\) when \(T = 10 K\).\textsuperscript{27} A unique feature that we have observed is that the Seebeck coefficient increases abruptly below the transition temperature while the resistivity decreases slightly. This behavior is rather unusual compared to the general trend that has been observed in other material systems. This unique trend has led to a large increase of the Seebeck and reduced resistivity is apparently related to the presence of electron–electron correlation. Although the values of the Seebeck coefficient and the power factor of our materials are low and lack commercial interest at this point of development, the enhancement percentages reported here are quite high (86\% in Seebeck and 245\% in power factor). Our findings suggest a potential enhancement mechanism for thermoelectric performance worthy of further investigation in future thermoelectric materials design.

Figure 4 shows the Seebeck coefficient over temperature \((S/T)\) as a function of one over conductivity \((1/\sigma)\) for (PbSe)\textsubscript{1\textsubscript{\downarrow}}(VSe\textsubscript{2})\textsubscript{1\textsubscript{\downarrow}} heterostructures. Under the assumption of weak electron–electron interaction, the Mott relation gives the Seebeck coefficient of a metallic system as

\[
S = -\frac{\pi^2 k_B^2 T}{3e} \frac{\partial \sigma}{\partial E_f}
\]
where $S$ is the Seebeck coefficient, $k_B$ is the Boltzmann constant, $T$ is the absolute temperature, $e$ is electron charge, and $\sigma$ is electrical conductivity. Equation 1 can be rewritten as

$$\frac{S}{T} = \left( -\frac{\pi^2 k_B^2}{3} \frac{d\sigma}{dE} \frac{1}{e} \right) \frac{1}{\sigma}$$  \hspace{1cm} (2)

Figure 4 contains a plot of $S/T$ vs $1/\sigma$ for both (PbSe)$_{1+x}$(VSe)$_2$ and (PbSe)$_{1+y}$(VSe)$_2$. In (PbSe)$_{1+x}$(VSe)$_2$, the $S/T$ versus $1/\sigma$ relationship is linear over the entire measured temperature range (80–300 K) as indicated by a black dotted line, indicating that $d\sigma/dE$ is roughly constant over this range. In addition, $d\sigma/dE$ can be written as $(d\sigma/dn)(dn/dE) = e\mu (dn/dE)$, where $e$ is electron charge, $\mu$ is the mobility, and $dn/dE$ is proportional to the density of states. For (PbSe)$_{1+x}$(VSe)$_2$, the $S/T$ vs $1/\sigma$ is similarly linear between room temperature and the CDW transition temperature of ~140 K, where the Mott relation is expected to be satisfied. Below 140 K there is a distinct change in behavior as the structure undergoes a structural distortion. The Mott relation is no longer valid below the CDW transition temperature because the conduction electron movements are highly correlated and no longer independent, and because the CDW transition is accompanied by a gap opening in the electronic structure to make the system nonmetallic.

Mavrokefalos et al. showed that the in-plane thermal conductivities of [(PbSe)$_{0.99}$(VSe)$_{2}$]$_x$, with $x = 2, 3, 4$ are around 0.5 W/mK at room temperature and are insensitive to interface density.\(^\text{[9,10]}\) For our (PbSe)$_{1+x}$(VSe)$_2$ heterostructures, the thermal conductivity could contain an appreciable electrical contribution since the VSe$_2$ layers are metallic. Figure S2 shows the estimated electrical contribution of the in-plane thermal conductivities $\kappa_{ll}$ of these two heterostructures based on the Wiedemann–Franz (WF) law using temperature-dependent resistivities data. Both heterostructures exhibit monotonically decreasing behavior as temperature decreases. At each temperature, the $\kappa_{ll}$ of (PbSe)$_{1+x}$(VSe)$_2$ is higher than that of (PbSe)$_{1+y}$(VSe)$_2$, due to the higher percentage of VSe$_2$ layers in the (PbSe)$_{1+x}$(VSe)$_2$ material. However, it should be noted that, for (PbSe)$_{1+x}$(VSe)$_2$ material, the WF law may not hold true when the temperature is below the CDW transition temperature.

In order to further probe the presence of structural change with respect to temperature, the in-plane diffraction patterns of the (PbSe)$_{1+x}$(VSe)$_2$ heterostructure were measured at several different temperatures (Advanced Photon Source, Beamline 33-BM). Figure S1a plots the in-plane lattice parameters of VSe$_2$ and PbSe as a function of temperature. A local minimum of lattice parameter of VSe$_2$ is observed when the temperature is around the CDW phase transition. The thermal expansion coefficient of VSe$_2$ in (PbSe)$_{1+x}$(VSe)$_2$ is about $10 \times 10^{-6}$/K between 140 to 300 K. This is approximately a factor of 2 smaller than the linear thermal expansion coefficient of bulk VSe$_2$ ($18.6 \times 10^{-6}$/K). However, below 140 K the thermal expansion coefficient is negative, at approximately $-30 \times 10^{-6}$/K. The thermal expansion coefficient of the PbSe layer remains constant over the entire temperature range and is within a factor of 2 found for bulk PbSe. The change in the thermal expansion coefficient of the VSe$_2$ constituent is consistent with a structural change occurring at ~140 K. Raman spectra of the (PbSe)$_{1+x}$(VSe)$_2$ and (PbSe)$_{1+y}$(VSe)$_2$ heterostructures taken at 77 and 300 K, shown in Figure S5, also suggest a structural change in the VSe$_2$ layer of (PbSe)$_{1+x}$(VSe)$_2$ as temperature is decreased. For the 1:1 heterostructure material, we see the emergence of several additional peaks in the Raman spectra at temperatures at 77 K, which is consistent with a transition to a lower symmetry...
lattice structure associated with the CDW of the VSe$_2$ constituent. As a control, the Raman spectra of the (PbSe)$_{1+x}$(VSe$_2$)$_2$ heterostructure do not show any temperature dependence. Previously, Balandin and co-workers reported similar changes in the temperature dependence of the Raman spectra of TiSe$_2$ corresponding to a CDW transition.\footnote{Hicks, L. D.; Dresselhaus, M. S. Use of Quantum-Well Franz–Keldysh Effects in the High Performance Oxide Thermoelectric Materials.} It should be noted that bulk VSe$_2$ exhibits a CDW transition with a much smaller change in resistivity above and below the CDW temperature. In (PbSe)$_{1+x}$(VSe$_2$)$_2$ and (PbSe)$_{1+y}$(VSe$_2$)$_2$, the VSe$_2$ layers have one or two adjacent PbSe layers rather than adjacent VSe$_2$ layers, and there will be charge transfer between the PbSe and VSe$_2$ layers. Both of these differences will change the CDW transition behavior of the VSe$_2$ layers relative to bulk VSe$_2$. The striking difference in behavior between the (PbSe)$_{1+x}$(VSe$_2$)$_2$ and (PbSe)$_{1+y}$(VSe$_2$)$_2$ materials is consistent with our previous measurements.\footnote{Hicks, L. D.; Harman, T. C.; Sun, X.; Dresselhaus, M. S. Use of Quantum-Well Franz–Keldysh Effects in the High Performance Oxide Thermoelectric Materials.}

\section*{CONCLUSION}

In conclusion, we report the temperature-dependent thermoelectric properties of (PbSe)$_{1+x}$(VSe$_2$)$_2$ and (PbSe)$_{1+y}$(VSe$_2$)$_2$ heterostructure materials. The (PbSe)$_{1+x}$(VSe$_2$)$_2$ material shows an increased Seebeck coefficient from 10.6 to 19.7 $\mu$V/K (85% increase) and increased power factor from 29.8 to 102.9 $\mu$W/mK$^2$ (245% increase) before and after the CDW phase transition, while the change in resistivity over the same temperature range is negligible. The (PbSe)$_{1+x}$(VSe$_2$)$_2$ phase transition, while the change in resistivity over the same temperature range is negligible. The (PbSe)$_{1+x}$(VSe$_2$)$_2$ material shows monotonically increasing values of the transport properties with temperature and lower values than those of the (PbSe)$_{1+y}$(VSe$_2$)$_2$ material. Above the CDW transition temperature, the $S/T$ vs $1/\sigma$ relationship is linear for both heterostructures in accordance with the Mott equation, which is valid for metals with weak electron–electron interactions. However, non-Mott behavior appears below the CDW transition for the (PbSe)$_{1+x}$(VSe$_2$)$_2$ material, resulting from the highly correlated conduction of electrons. Furthermore, temperature-dependent in-plane XRD and Raman spectra indicate unique structural changes for the (PbSe)$_{1+x}$(VSe$_2$)$_2$ heterostructure film. The mechanism underlying these results may be used to provide a new approach for enhancing the thermoelectric performances of materials at low temperatures.

\section*{ASSOCIATED CONTENT}

\section*{Supporting Information}

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.0c02882.

Temperature-dependent basal plane area of (PbSe)$_{1+x}$(VSe$_2$)$_2$ measured by in-plane X-ray diffraction; estimated thermal conductivities of (PbSe)$_{1+x}$(VSe$_2$)$_2$ and (PbSe)$_{1+y}$(VSe$_2$)$_2$ materials based on the Wiedemann–Franz (WF) law (PDF)

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Notes

The authors declare no competing financial interest.

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