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II-VI Organic-Inorganic Hybrid Nanostructures with Greatly Enhanced Optoelectronic Properties, Perfectly Ordered Structures, and Shelf Stability of Over 15 Years

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ABSTRACT: Organic-inorganic hybrids may offer material properties not available from their inorganic components. However, they are typically less stable and disordered. Long-term stability study of the hybrid materials, over the anticipated lifespan of a real-world electronic device, is practically nonexistent. Disordering, prevalent in most nanostructure assemblies, is a prominent adversary to quantum coherence. A family of perfectly ordered II-VI-based hybrid nanostructures has been shown to possess many unusual properties and potential applications. Here, using a prototype structure β -ZnTe(en)_{0.5}—a hybrid superlattice—and applying an array of optical, structural, surface, thermal, and electrical characterization techniques, in conjunction with densityfunctional theory calculations, we have performed a comprehensive and correlative study of the crystalline quality, structural degradation, electronic, optical, and transport properties on samples from over 15 years old to the recently synthesized. The findings show that not only do they exhibit an exceptionally high level of crystallinity in both macroscopic and microscopic scale, comparable to high-quality binary semiconductors; and greatly enhanced material properties, compared to those of the inorganic constituents; but also, some of them over 15 years old remain as good in structure and property as freshly made ones. This study reveals (1) what level of structural perfectness is achievable in a complex organic-inorganic hybrid structure or a man-made superlattice, suggesting a nontraditional strategy to make periodically stacked heterostructures with abrupt interfaces; and (2) how the stability of a hybrid material is affected differently by its intrinsic attributes, primarily formation energy, and continued...

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Figure 1. Optical spectroscopy signatures of β -ZnTe(en)_{0.5} at different degradation stages. (a) Crystal structure viewed along the *a*-axis and *c*-axis. (b) Photoluminescence spectra. (c) Raman spectra of low wavenumber region. (d) Raman spectra of large wavenumber region. (e) Raman spectra of pristine and partially degraded areas adjacent to each other (inset: Raman mapping of the Te mode showing no sign of degradation in the green area but partial degradation in the red area).

extrinsic factors, such as surface and defects. By correlating the rarely found long-term stability with the calculated relatively large formation energy of β -ZnTe(en)_{0.5} and contrasting with the case of hybrid perovskite, this work illustrates that formation energy can serve as an effective screening parameter for the long-term stability potential of hybrid materials. The results of the prototype II–VI hybrid structures will, on one hand, inspire directions for future exploration of the hybrid materials, and, on the other hand, provide metrics for assessing the structural perfectness and long-term stability of the hybrid materials.

KEYWORDS: organic-inorganic hybrids, long-term stability, structural ordering, optical properties, degradation mechanism

rganic–inorganic hybrid materials have been explored for a wide range of applications, because of their added and enhanced properties, compared to their inorganic counterparts.^{1–6} Among them, hybrid halide perovskites (e.g.,

MAPbI₃, where MA = CH_3NH_3) are perhaps the most extensively and intensively studied hybrid materials, because of their extraordinary application potentials in a wide range of applications, in particular photovoltaics (PV) and solid-state lighting (SSL). However, hybrid materials typically exhibit two major drawbacks: (1) lower long-term stability than inorganic compounds; and (2) structural disorder. These two characteristics make them distinctly different from typical crystalline inorganic semiconductors and related nanostructures.

Understandably, systematic long-term stability studies of hybrid materials are rare in general, if any, since they typically do not last long. By long-term, we mean a time scale of one or two decades that is typically expected for (opto-)electronic applications. Long-term stability and high melting points of familiar semiconductors such as Si and GaAs are intrinsically associated with their large formation energies. However, extrinsic effects, such as surface and defects, often affect their stability under ambient conditions. Luckily, for many crystalline inorganic materials, the oxidation is usually a self-limiting process, which ensures their long-term stability. Hybrid perovskites are known to have relatively poor long-term stability, both under ambient conditions⁶ and illumination,⁷ which limits the scope of their applications. Despite the major improvement in stability from hours just a few years ago⁷ to currently up to a couple of months, benefitting from a reduction in structural defects and surface passivation,^{8–10} and some 2D versions show moderately better stability,^{11,12} they remain inadequate for general PV and SSL applications. The degradation mechanisms are not yet well understood. It has been shown theoretically that the hybrid perovskite MAPbI₃ has very low or even negative formation energy $(\pm 0.1 \text{ eV})$.^{13,14} Would this place a limit on how much further improvement is attainable? There is neither a reliable theoretical method to predict the long-term stability of a hybrid material nor a hybrid material with demonstrated longterm stability that can serve as an example to show the necessary characteristics. Indeed, can a hybrid with a larger formation energy offer long-term stability? What would the roles of the extrinsic effects be in that case? Therefore, investigating the long-term evolution of a hybrid material that does have good long-term stability becomes critically important and highly appreciated.

Hybrid perovskites are considered as crystalline materials in the sense that they have excellent long-range order. Nevertheless, they are structurally disordered in short-range in their room-temperature phases^{15,16} and, therefore, are not crystals in the genuine sense. One might think that, for inorganic nanostructures, the simplest cases-semiconductor superlattices—are easier to achieve perfect crystal structures. In reality, although it has been over five decades, since the proposal of the superlattice concept,¹⁷ the holy grail of the superlattice, a structure without interdiffusion between the adjacent monolayers of the constituents, remains elusive, even for the best studied examples $(GaAs)_n/(AlAs)_m$ and $(GaP)_n/(InP)_m$.^{18–20} Although disordering can be beneficial for some applications,^{16,21} it diminishes quantum coherence, which is required for various advanced applications, such as quantum optics,²² and it has a negative effect on many basic material properties, such as exciton dynamics and electronic conductivity.²³ Therefore, a synthesis approach that can yield a perfectly ordered nanostructure array will be of both fundamental and practical interest.

The II–VI-based hybrid nanostructures were first reported in 2000,²⁴ including a large number of combinations of II–VI compounds and molecules, as well as distinctly different structure types.²⁵ As a prototype structure, β -ZnTe(en)_{0.5} (en = C₂N₂H₈, ethylenediamine) consists of two-monolayer-thick ZnTe (110) slabs interconnected by en molecules forming

covalent-like bonding through Zn and N atoms,²⁴ as shown in Figure 1a. Although it is a crystal on its own with subnanometerscale integration of the organic and inorganic components, it can nevertheless be viewed as a hybrid superlattice with the molecule serving as electronic barriers, as well as dielectric confinement layers.²⁶ In contrast to the inorganic superlattices and most other hybrid materials, this hybrid superlattice is a perfectly ordered structure microscopically. It has both long and shortrange order,²⁴ because the organic molecules all stay in welldefined configurations, and the interdiffusion between the inorganic and organic layers is not possible, because of their vastly different structures. β -ZnTe(en)_{0.5} has been shown to have crystallinity comparable to most high-quality elemental and binary semiconductors, e.g., a low-temperature Raman line width below 1 cm^{-1} .^{25,27} More interestingly, it exhibits various desirable properties, e.g., room-temperature excitonic emission due to a large exciton binding energy estimated to be over 200 meV, strongly enhanced optical absorption as high as 10⁶ cm^{-1,26} broad-range zero-thermal expansion,²⁷ much-reduced density and dielectric constants,²⁶ and greatly reduced thermal conductivity.²⁸ These properties suggest several potential applications, including room-temperature exciton-polariton condensation, optical switching, efficient UV emission and detection, and thermoelectrics. It has recently been demonstrated that one could even exfoliate the thin inorganic slabs individually from these II-VI hybrids.²⁹ These attributes make β -ZnTe(en)_{0.5} an ideal prototype system for revealing the pertinent mechanisms dictating the long-term stability of hybrid materials and general design principles to achieve highly ordered hybrid structures. This work conducts a systematic investigation for β -ZnTe(en)_{0.5} to reveal how practically perfect structural ordering, in both a macroscopic and microscopic sense, is manifested in its structural and electronic characteristics, and how the intrinsic and extrinsic mechanisms affect its structural and physical properties over one and a half decades.

RESULTS AND DISCUSSION

Structural Ordering, Optical Properties, and Stability **Probed by Optical Spectroscopy.** β -ZnTe(en)_{0.5} is an orthorhombic crystal with space group Pnnm, point group D_{2h}, and stacking axis *b* and in-plane axes *a* and *c*, typically found as a thin crystal plate with the b-axis aligned with the normal.^{24,26} Pristine β -ZnTe(en)_{0.5} is a transparent crystal with a bandgap 3.719 eV at 1.5 K.²⁶ It exhibits distinctly different optical properties from those of ZnTe. Figures 1b-d, respectively, compare the spectra of photoluminescence (PL) excited at 325 nm and Raman excited at 532 nm (in small and large frequency regions) of the hybrid samples in pristine and varying degree of degradation states, with comparison to those of ZnTe. In Figure 1b, the PL spectrum of a fresh-made sample S19-p (here, "19" denotes the year of synthesis (2019), and "p" stands for pristine) shows only a single peak (I_{ex}) at 3.569 eV of free exciton emission.²⁶ This hybrid crystal is free of below bandgap defect emission, which is in stark contrast to most high bandgap inorganic semiconductors such as GaN and ZnO, where below bandgap defect emission is almost inevitable.^{30,31} In Figure 1c, the Raman spectrum of S19-p, measured in a backscattering geometry along the *b*-axis and parallel polarization configuration of 45° between *a*- and *c*-axes to reveal a maximum number of Raman modes intrinsic to the hybrid structure, exhibits multiple sharp peaks similar to those reported previously²⁷ but with two additional lower frequency modes (see Table S1 for Raman mode frequencies and symmetries). The symmetry assignments



Figure 2. Comparison between recently synthesized (S19-p) and aged (S07-p) sample in PL and vertical electrical conductivity. (a) Large wavelength range PL spectra (S07-p is vertically displaced for clarity), (b) PL intensity versus excitation density, and (c) I-V characteristic (dots represent data, lines represent fitting curves).

were obtained by DFT calculations of phonon modes and their Raman tensors. Despite being a much more complex structure (32 atoms/unit cell), the Raman line widths (measured by full width at half-maximum, fwhm) of the hybrid is comparable to that of ZnTe: e.g., 3.2 cm^{-1} vs. 3.7 cm^{-1} between the strongest hybrid mode at 133.2 cm⁻¹ and ZnTe 1LO at 205.8 cm⁻¹, indicating a high degree of structural ordering in the hybrid. The Raman spectrum of S19-p in the higher-frequency region is shown in Figure 1d. Because of the strong bonding between the ZnTe sheets and en molecules, the ordering also reflects on the en-derived Raman modes, where the en modes (see Table S1 in the Supporting Information for details) are typically shifted in frequency but substantially narrower, compared to those of freestanding en, 32 for instance, 2869 cm⁻¹ (fwhm = 5) vs. 2860 cm⁻¹ (fwhm = 36). Note that β -ZnTe(en)_{0.5} studied here has less Raman modes in the high-frequency region than α -ZnS(en)_{0.5} measured previously,³³ because the α -phase has twice as many atoms in the unit cell.

Many aged samples were measured under the same conditions. Quite remarkably, the same intrinsic PL and Raman spectra were observed in some samples that were more than a decade old, although the aged samples often exhibited varying degrees of degradation, manifested as changes in both PL and Raman spectrum. They fall into three groups: (1) pristine, showing practically identical optical spectra as S19-p, (2) degraded, showing no intrinsic hybrid spectroscopy features but those of the degradation products, and (3) partially degraded, showing the spectroscopy features of both (1) and (2). Representative results are shown in Figure 1. For example, S07-p, typical from a batch of crystals, exhibits almost-identical spectroscopy signatures of S19-p, as shown in Figure 1b for PL and Figures 1c and 1d for Raman. Typical PL and Raman spectra for a partially degraded sample (S07-pd) and severely degraded sample (S06-d) are shown in Figures 1b, 1c, and 1d, respectively. They show, in PL, the weakening or disappearance of the bandedge emission peak and appearance of a broad below bandgap emission band (I_D) , whereas in Raman, they show the weakening or disappearance of the hybrid Raman modes, and most noticeably the appearance of Raman modes related to metallic Te at ~124 and 142 cm^{-1.34} Degradation is often nonuniform over the surface area of a crystal. For instance, the intrinsic Raman features were observed in some even older samples, such as S03-m (where "m" stands for mixed states of degradation), where adjacent pristine and partially degraded

regions coexisted, as shown in Figure 1e. Similar spatial variation was also observed in a bulk hybrid perovskite crystal,⁷ but the overall degradation occurred in a totally different time scale. Although β -ZnTe(en)_{0.5} is still not as stable as inorganic semiconductors such as Si and GaAs, it is far more stable than most known hybrid materials, and some of them even have a shelf life of over one and half decades! More significantly, these findings indicate that the observed structural degradation may not even be intrinsic in nature but rather due to some extrinsic mechanisms, as indicated by the variation in shelf life between different samples, and the nonuniform degradation on a single sample.

To further examine the microscopic scale crystallinity and how it might be affected by aging, a more-detailed comparison in PL and electrical conductivity between S19 and S07 is provided in Figure 2. Figure 2a depicts their PL spectra in a larger range up to 1200 nm, showing minimal below bandgap PL emission over the entire range, which indicates that there are very few radiative defect centers in the materials. The influence of the potential nonradiative defect centers can be effectively probed by the excitation density dependence of PL intensity over a large range of excitation density.^{16,35} Indeed, as shown in Figure 2b, when the excitation density (p) is varied by six orders, both S19 and S07 exhibit a very close to linear dependence ($I \propto p^n$, where n = 0.98 ± 0.01 for S19 and 1.01 ± 0.01 for S07), implying an internal quantum efficiency of ~100%, superior to the best reported for CdTe, GaAs, and hybrid perovskite.¹⁶ Furthermore, S19 and S07 are found to have very similar electron mobilities along the *b*-axis or vertical direction, $2.5 \times 10^{-3} \text{ cm}^2/(\text{V s})$ for S19 and 8.8 \times 10⁻³ cm²/(V s) for S07, when their I–V characteristics, shown in Figure 2c, are fit with the Mott-Gurney model for the space-charge-limited current.³⁶ These mobility values are relatively low, compared to conventional inorganic semiconductors, which is perhaps understandable for the conductivity along the stacking direction, but nevertheless significantly higher than the mobilities in most organic materials.³⁷ The approximate linear dependence of $I \propto V^2$ indicates that the material is highly insulating with minimal free carriers, as expected by the Mott-Gurney law. These results further confirm that the materials have very little either radiative or nonradiative defect centers, thus, a very high degree of crystallinity in microscopic scale, and may retain the high crystallinity for well over a decade.



Figure 3. XRD and Raman characterization of pristine and seemly degraded samples. (a) *b*-axis XRD 2θ scans for S19-p, S07-p, and S03-d. (b and c) High-resolution XRD rocking curves or ω scans and 2θ scans, respectively, at (0,2,0) reflection for the three samples. (d) Raman spectra of S03-d measured from the cleaved edge at locations close and away from the surfaces (insets show Raman mapping of the Te mode, overlaid with the optical image, on the cleaved edge near the upper and lower surface of the crystal, where the dashed lines indicate the sample surfaces).

We also note that β -ZnTe(en)_{0.5} exhibits considerably better photostability than MAPbI₃. In air with prolonged exposure to above bandgap excitation, the former has a degradation threshold ~300 W/cm², and the latter ~10 W/cm², ¹⁶ compared to CZTSe (~3 × 10⁴ W/cm²) and Si (>10⁶ W/cm²).³⁸

Crystallinity and Stability Probed by X-ray Diffraction. It was puzzling that judged by the optical signatures, samples like S06-d were severely degraded, but visually they remained intact. Thus, we performed XRD studies on a few pristine and "degraded" samples used in the optical studies. It turned out that these "degraded" samples still gave rise to the same crystal structure as the pristine sample based on the XRD powder diffraction analyses: for instance, nearly identical (*a*, *b*, *c*) lattice constants between S19-p and S06-d (see detailed comparisons in Table S2 in the Supporting Information).

We further performed HRXRD measurements on selected pristine and "degraded" samples. Figure 3a shows very similar (0n0) single-crystal diffraction peaks between S19-p, S07-p, and S03-d, except for the (020) peak of S03-d being significantly weaker (see Table S3 in the Supporting Information for tabulated relative intensities with comparison to simulated results). They all exhibit a very high degree of macroscopic crystallinity, as indicated by the single-crystal XRD results of rocking curve or ω scan line widths $(W_{\rm RC})$ and ω -2 θ coupled scan line widths $(W_{2\theta})$. Roughly speaking, $W_{\rm RC}$ measures the lateral uniformity of the crystalline structure, and $W_{2\theta}$ reflects the uniformity of lattice spacing along the stacking direction. For the (020) diffraction, $W_{\rm RC} = 22''$ and $W_{2\theta} = 38''$ for S19-p, as shown in Figures 3b and 3c, respectively, compared to the results of a high-quality ZnTe single crystal with $W_{\rm RC}$ = 19" and $W_{2\theta}$ = 16.5" for the (002) diffraction.³⁹ For comparison, the best reported

 $W_{\rm RC}$ is 35" for bulk MAPbI₃⁴⁰ and 30" for epitaxially grown GaN.⁴¹ Interestingly, the $W_{\rm RC}$ results of S07-p and S03-d are very similar, 35" and 31", respectively. The XRD results of S03-d suggest that despite the signs of degradation in optical spectroscopy, the hybrid samples retained the same crystal structure as a whole. Keep in mind that the millimeter-sized Xray beam not only averaged over the entire sample area (typically a few hundred micrometers) but also the entire thickness (typically $10-20 \ \mu m$), whereas the spectroscopy measurements were performed with a confocal optical system that only probed a small volume near the sample surface (on the scale of 1 μ m). Raman depth profiling was conducted for the degraded sample using 532 nm laser that is supposed to be transparent to the pristine material, but the Raman signal decayed quickly into the sample, suggesting the surface region of the degraded sample was highly absorptive to this below the bandgap wavelength.

We then cleaved a severely degraded crystal S03-d and performed Raman mapping on the newly exposed edge, shown as an inset in Figure 3d. It turned out that the body of the ~20- μ m-thick crystal exhibited the same Raman modes as a pristine sample, and only the regions ~2 μ m thick from the top and bottom surface were degraded, as shown in Figure 3d. The results explain the puzzling "inconsistency" between the optical and XRD results, including the weakened (020) peak of S03-d, corresponding to the largest incidence angle at which more surface region was probed. The observation of the Te modes from the surface region of the "degraded" hybrid is similar to thermally oxidized ZnTe where the top layer consists of amorphous ZnO and nanoscale Te domains.⁴² The observations seem to suggest that the degradation of the hybrid is caused by surface oxidation, as to be confirmed next, which occurs in most

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Figure 4. SEM and XPS surface characterization and analyses. (a-e) SEM images of a fresh sample (S19-p) (panel (a)), an aged sample showing very little degradation optically (S07-p) (panel (b)), an aged sample optically showing severe degradation (S03-d) (panel (c)), a thermally degraded fresh sample (S19-th) (panel (d)), and single-crystalline ZnTe (panel (e)). (f-h) XPS spectra at different etching times or depths of sample S19-p (panel (f)), sample S06-d (panel (g)), and ZnTe (panel (h)).

nonoxide semiconductors. We may further speculate that a terminating layer of en molecules might prevent the surface from oxidation, which is a self-passivation effect. However, the oxidation process might be initiated at a defective surface or a region with structural defects. This understanding is consistent with the observed variation in shelf life and degradation inhomogeneity. We have also noticed that the edges of a newly synthesized crystal have a tendency to degrade faster than the top surface, because the edges are not terminated by en molecules (see Figure 1a).

Stability Probed by Surface Analyses. To verify the oxidation process and degradation mechanism, we performed surface analyses using scanning electron microscopy (SEM), energy-dispersive X-ray (EDX) analysis, and X-ray photoelectron spectroscopy (XPS) on multiple pristine and "degraded" samples. Figure 4a–e shows the SEM images obtained for S19-p, S07-p, S03-d, and S19-th (thermally oxidized at 190 °C for 20 min), and ZnTe, respectively, taken from smooth and clean areas of the samples where optical measurements were conducted. The O:Zn ratio obtained from the EDX analysis is shown with each SEM image. The original EDX spectra are depicted in Figure S1 in the Supporting Information. The comparison reveals a steady increase in oxygen content on the surface with increasing level of degradation, for instance, O:Zn = 0.05 for S19-p and 1.08 for S03-d. These results qualitatively support the proposed degradation mechanism of surface oxidation.

XPS data further corroborate the above results. We measured depth-resolved XPS spectra for S19-p, S06-d, and ZnTe by applying *in situ* Ar etching, with the results shown, respectively,



Figure 5. Thermal degradation of freshly made sample (S19-p) in air and in a N_2 environment probed by Raman and thermogravimetric analysis (TGA): (a) *in situ* Raman spectroscopy in air, (b) *in situ* Raman spectroscopy in N_2 , (c) Raman spectra at room temperature after being heated to 500 °C in air and N_2 then returning to room temperature, and (d) TGA in air and N_2 (inset shows the low-temperature region).

in Figures 4f-h near the energies of two Te 3d transitions. Additional scans of a broader energy range can be found in Figure S2 in the Supporting Information. For S19-p, on the nonetched surface, two peaks were observed, at 576.5 eV $(3d_{5/2})$ and 586.9 eV $(3d_{3/2})$, similar to a naturally oxidized ZnTe in air, as reported in the literature;⁴³ after etching, two new peaks emerged on the lower energy sides, respectively, at 573.8 eV (δE = -2.7 eV) and 584.2 eV (δE = -2.7 eV), and after about 15 s etching (or removal of \sim 150 nm of the top layer), the high energy peaks disappeared and the new peaks reached saturated intensities. Similar shifts were observed in ZnTe, but the transition energies for pure ZnTe are slightly lower than in the hybrid, by ~ 0.8 eV. The difference can be understood by the fact that the Te bonding situations are different in the two structures: with each Te bonding to only three Zn in the hybrid and four Zn in ZnTe. For the severely degraded sample, a similar trend was observed, but a much longer etching time (170 s, approximately corresponding to a depth of 1.7 μ m) was required to reach a steady state, which suggests a thicker oxidized layer on this severely degraded sample and is consistent with the cleaved edge Raman results (Figure 3d). The remaining weak oxidation peaks after etching indicates that oxidation might have somewhat penetrated into the deeper volume of the crystal. Note that, similar to XRD, XPS probes a large area, because of its macroscopic beam size; therefore, the results could be affected by the embedded extended defects and surface contamination, whereas micro-Raman and EDX are able to analyze visually perfect regions. We note that even the new sample S19-p had a thin oxide layer, although showing no effect in optical spectroscopy after being kept in air for one year. The existence

of the pristine area in S03-m seems to suggest that the oxidation process is self-limiting, if no structural defects, as in most nonoxide inorganic semiconductors.

Thermal Stability in Different Environments. Thermal stability is important for device application, because of a self-heating effect under the operation condition. Thermal stability study was performed in both air and N₂-protected conditions on newly made crystals (S19-p) in two ways:

- By heating one single piece of the crystal using a heating stage with a small heating chamber from 40 to 500 °C while monitoring with Raman spectroscopy *in situ*.
- (2) By performing thermogravimetric analysis (TGA) to a collection of small crystals.

These two experiments are similar in the sense that, in both cases, a material property is probed when the sample temperature is raised in a small step and held steady briefly at each step to take the measurement; however, in the former case, a Raman spectrum is measured versus the weight in the latter case.

In Raman, a significant difference in thermal degradation was observed between heating in air or N₂ until ~150 °C. Figure 5a shows the evolution of the Raman spectra while heated in air (spectra at more temperature points can be found in Figure S3 in the Supporting Information), where the Te peaks start to grow at ~160 °C, and the hybrid peaks vanish at >210 °C, mimicking an accelerated degradation process under ambient conditions. Figure 5b shows the results under N₂ protection (more spectra are shown in Figure S3). In this case, no or very little Te-related Raman signals can be observed for temperatures up to 300 °C; but at ~230 °C, the ZnTe LO phonon starts to emerge (see

Figure S3). When brought back to room temperature after being heated up to 500 °C, the sample exhibits the characteristic multiple LO phonon resonant Raman modes of a somewhat defective $ZnTe^{39}$ (Figure 5c), which is similar to the report where thermal annealing of $ZnS(en)_{0.5}$ at 600 °C under vacuum yielded ZnS.⁴⁴ However, if heated in air, no ZnTe is found in the degradation product either at high temperature (up to 400 °C, Figure 5a) or after returning to room temperature (Figure 5c), where, instead, a mixture of Te and TeO₂ is seen.⁴⁵ Thus, N₂, to a large extent, prevents the oxidation process, and the process reflects the intrinsic degradation path: the evaporation of en molecules. The finding provides guidance to the acceptable operating temperature of a potential device using this material with proper encapsulation to minimize the oxidation.

The TGA results, shown in Figure 5d, are qualitatively consistent with the spectroscopy results but offer more insight. Initially until ~230 °C, both curves show slow mass reduction, but the curve in N_2 is slightly faster (inset of Figure 5d), which can be explained by the fact that, while ligand evaporation or calcination occurs due to heating in both cases, in air, the mass loss is composed partially by oxidation. The TGA curve in N₂ shows a continual decrease but is accelerated near 290 °C, reaching a plateau before 400 °C, corresponding to the complete conversion into ZnTe, which matches the mass loss of the molecules (about 13% in weight). In contrast, in air, significant mass loss does not occur until ~200 °C, and at ~290 °C, the curve actually begins to increase, incdicating that the oxidation process is accelerated; and the mass gain saturates at ~600 °C. We may understand the intriguing curve as a convoluted effect of multiple competing oxidation processes: $ZnTe(en)_{0.5} \rightarrow$ $ZnTeO_2$, where $ZnTeO_2$ is predominantly a mixture of ZnO +xTe + yTeO + zTeO₂ (x + y + z = 1), where the highest point matches ZnO + 0.5Te + 0.5TeO2. The detailed analyses are given in Figure S4 in the Supporting Information, although the exact degradation process requires further study.

We may have a unified picture for the thermal degradation: following the initial loss of en near the surface, the molecules in the body start to leave at \sim 290 °C, and at close to 400 °C, the hybrid is fully degraded, resulting in different products in different environments.

Although naturally occurring slow degradation can be mimicked to some extent by an accelerated process (heating in air): the heating process is not able to reveal some subtle, often extrinsic, effects that actually happened in the real process, such as the region-to-region or sample-to-sample variations. It is also nontrivial to establish a reliable quantitative correlation of the thermal degradation temperature with the shelf life of the material other than the qualitative correlation. This work has provided one correlated study.

Formation Energies: DFT Calculation and Experiment. The formation energy of β -ZnTe(en)_{0.5} was calculated by $\Delta E = E[\beta$ -ZnTe(en)_{0.5}] $- E[ZnTe] - 1/2E[C_2N_2H_8]$, which is relevant to the intrinsic degradation path mentioned above, where $E[\beta$ -ZnTe(en)_{0.5}] is the total energy per formula unit of β -ZnTe(en)_{0.5}, E[ZnTe] is the total energy per formula unit of ZnTe in zinc-blende structure, and $E[C_2N_2H_8]$ is the total energy of the $C_2N_2H_8$ molecule. The calculated formation energy is the dissociation energy without including the kinetic barrier. The calculation has yielded $\Delta E = -0.52$ eV per formula, compared to -0.80 eV of the formation energy of ZnTe (typical for II–VI compounds), and is much greater than that of (CH₃NH₃)PbI₃, in the range of ±0.1 eV.^{13,14} Formation energy is the lower bound of the thermal activation energy of the intrinsic thermodynamic degradation process. The kinetic barrier between the degradation products and the hybrid state is also relevant, particularly when the formation energy is very small, such as in the case of the hybrid perovskite where the kinetic barrier plays a critical role in stabilizing the structure.⁴⁶ The situation resembles the chemical reaction described by a well-known transition state theory. A sufficiently large formation energy may be viewed as a necessary condition for the desired level of long-term stability, because it describes the thermodynamics stability under vacuum or in a protected environment. A thermodynamically stable structure may still be environmentally unstable, such as silicene, which is stable under vacuum but usually oxidized very quickly in air.⁴⁷ The observed long-term stability in part of S03-m and in S07-p implies that surface oxidation can be self-limited under favorable growth conditions, for instance, when the surface is uniformly passivated by the organic molecules.

To gain further insight into the potential intrinsic long-term stability, we have measured the degradation time of β - $ZnTe(en)_{0.5}$ in elevated temperatures between 210 $^\circ C$ and 270 °C by monitoring the 133 cm⁻¹ Raman mode intensity versus time at each set temperature. The Raman data of Figure 5b could be viewed as the results at time $t \approx 0$. The intensity exhibits exponential decay with time, which reveals a temperature-dependent decay rate. The degradation rate may be defined as $k(T) = 1/t_{1/2}$, where $t_{1/2}$ is the half intensity point. Assuming $k(T) = A \exp(-E_A/(kT))$, fitting the experimental data has yielded $E_A = 1.63 \pm 0.06$ eV. The details can be found in Figure S5 in the Supporting Information. The difference between the measured activation energy and the calculated formation energy could be explained as the kinetic energy barrier height (\sim 1.11 eV). This study suggests that the intrinsic shelf life (from the extrapolated $t_{1/2}$ at 25 °C in N₂) of this material could be as long as 1.44×10^8 years.

Further Discussion. Generally, the stability includes three key aspects:

- (1) The *intrinsic effect*, namely, the material formation energy calculated as an infinite crystal, which is expected to be smaller for a hybrid material than its inorganic component. Thus, the consideration lies in whether the binding strength of the hybrid material is adequate for the intended application condition (e.g., operation temperature).
- (2) The surface or edge effect, which is most relevant to the chemical stability of the material, where degradation can initiate through processes, such as oxidation and/or evaporation of the terminating molecules.
- (3) The *structural defects*, which may provide easier paths for degradation.

The substantial variation in shelf life from sample to sample even between different regions within one sample indicates that the observed degradation might not be intrinsic in nature, but may be associated with surface imperfection or structural defects. Nonuniform degradation often occurs in inorganic semiconductors due to the spatial variation in defect condition, for instance, in GaAs⁴⁸ and CZTSe.³⁸ The detailed degradation paths of the hybrids under different environments require further studies. The most aged sample (S03-m) still showing the pristine spectroscopy features suggests the lower bound of the thermodynamically determined material lifetime to be ~16 years, although the thermal degradation study indicates that it could be much longer.

 β -ZnTe(en)_{0.5} can be viewed as one of the most perfect manmade superlattices and the only hybrid superlattice that has been carefully investigated. It also represents a structure with unusual chemical bonding (i.e., 3-fold bonded Te atoms) yet without the detrimental effects of dangling bonds. Despite the structure complexity, a hybrid material can have a very high degree of crystallinity, manifested in both macroscopic structural properties (e.g., XRD line width) and microscopic properties (e.g., defect emission). This attribute can offer much-needed quantum coherence for electronic processes in next-generation (opto)electronic technologies. This and other related II-VIbased hybrids demonstrate a totally different approach for forming a perfectly abrupt heterostructure, that is, combining two structures with drastically different materials, instead of two structurally similar ones, to eliminate the intermixing that occurs in most conventional heterostructures. An inorganic analogue is the abrupt interface between rock-salt PbTe and zinc-blende CdTe along their [111] direction.⁴⁹

CONCLUSIONS

By providing a comprehensive characterization of one prototype system, β -ZnTe(en)_{0.5}, with some samples being monitored over 16 years, this work illustrates the interplay of intrinsic and extrinsic degradation mechanisms in determining the long-term stability of an organic-inorganic hybrid material. Benefiting from its relatively large intrinsic formation energy as well as a large kinetic barrier, and stable surface, even without encapsulation, β -ZnTe(en)_{0.5} has been shown to exhibit a shelf life of over 15 years, whereas its intrinsic lifetime could be as long as 10⁸ years. The observed deterioration of structural integrity is actually caused primarily by the extrinsic effects, such as surface imperfection, exposed edge, and structural defects. This study indicates that formation energy can serve as an effective screening parameter for the long-term stability prospective of a new hybrid material. However, when the formation energy is adequately high, extrinsic degradation paths could be practically more significant for the long-term stability of the hybrid.

 β -ZnTe(en)_{0.5} also exhibits exceptionally high degree of both macroscopic and microscopic scale structural perfectness, manifesting as small XRD and Raman line widths comparable to the high-quality ZnTe and near 100% internal PL quantum efficiency superior to most known high bandgap inorganic semiconductors, such as ZnO and GaN.

The success in the synthesis of these practically perfect hybrid superlattices demonstrates a nonconventional strategy to achieve periodic stacking of heterostructure materials with abrupt interfaces and offers a more practical method to controllably stack ultrathin 2D layers to achieve desirable overall thickness to meet a specific application need.

This study provides practical guidance for selecting different organic—inorganic hybrid materials to suit different application needs, and it reveals the potentials of the II–VI-based hybrids for a wide range of scientific explorations and applications with excellent long-term stability.

MATERIALS AND METHODS

Materials. New samples of β -ZnTe(en)_{0.5} were synthesized following slight modifications of previously reported literature procedures.²⁴ Zn(NO₃)•6H₂O(595mg, 2 mmol), Te (128 mg, 1 mmol), and ethylenediamine (6 mL) were placed in a Teflon-lined stainless steel high-pressure acid digestion vessel (Parr, Model 4746). The vessel was placed in a muffle furnace set at 200 °C for 3 days. After

slow cooling to room temperature, the resulting product mixture was filtered and washed with distilled water, 95% ethanol, and diethyl ether, then dried in air to produce colorless platelike crystals. The samples used in this work are labeled as Sxx-y, where xx indicates the year of synthesis (e.g., "03" for 2003), and y indicates the degradation status (e.g., "p" for pristine, "d" for degraded). Samples labeled as S19-p were from one newly synthesized batch. The oldest samples (2006 or earlier) were the same pieces mounted on their sample holders used in previous studies, $^{25-27,50}$ and the 2007 samples were from one synthesis batch and were not studied previously. The majority of S07 showed no sign of degradation, with a few exceptions (e.g., S07-pd). The aged samples were stored under ambient conditions until they were (re)measured recently.

Optical Characterization. Raman and PL measurements were performed on a Horiba LabRam HR800 confocal Raman microscope with a 1200 g/mm grating. For Raman, a 532 nm laser beam was focused on the sample surface using a long-working-distance 50× microscope lens with NA = 0.5. The laser power focused onto the sample was $125 \pm 10 \,\mu\text{W} (\sim 9.4 \times 10^3 \,\text{W/cm}^2)$. For PL, the sample was excited by a 325 nm laser beam, which was focused through a 40× UV microscope lens with NA = 0.5. The laser power delivered to the sample was $15.5 \,\mu\text{W} (\sim 3.1 \times 10^3 \,\text{W/cm}^2)$.

Electrical Characterization. Vertical conductivity measurements were performed for S19-p and S07-p. The I-V scan was done by using a Keithley Model 2401 Source Meter Unit, with Keithley Kickstart software. The sample with a surface normal along the *b*-axis was placed on a chip carrier that provided the bottom contact. Tungsten probe tip (of 50 μ m in diameter) was placed directly on the sample surface as the top contact. Multiple samples were measured for each batch of the samples with fluctuating results likely due to inconsistency in contacts. The data shown represent approximately the best achieved results for the respective batches of the samples. The I-V characteristic was fit to Mott-Gurney law:³⁶

$$J = \frac{9}{8} \varepsilon \varepsilon_0 \mu \frac{V^2}{L^3}$$

where *J* is the current density, ε the dielectric constant of β -ZnTe(en)_{0.5} ($\varepsilon \approx 6$), μ the carrier mobility, and *L* the sample thickness (L = 6 and 10 μ m, respectively, for S19-p and S07-p with ~10% accuracy).

Structural Characterization. X-ray crystallography data were acquired with an Agilent (now Rigaku) Gemini A Ultra diffractometer. Crystals of suitable size were coated with a thin layer of paratone-N oil, mounted on the diffractometer, and flash-cooled to 105 K in the cold stream of the Cryojet XL liquid nitrogen cooling device (Oxford Instruments) attached to the diffractometer. The diffractometer was equipped with sealed-tube long fine focus X-ray sources with a Mo target ($\lambda = 0.71073$ Å) and a Cu target ($\lambda = 1.5418$ Å), four-circle kappa goniometer, and CCD detector. CrysAlisPro software was used to control the diffractometer and perform data reduction. The crystal structure was solved with SHELXS. All non-hydrogen atoms appeared in the E-map of the correct solution. Alternate cycles of model building in Olex2 and refinement in SHELXL followed. All non-hydrogen atoms were refined anisotropically. All hydrogen atom positions were calculated based on idealized geometry and recalculated after each cycle of least-squares. During refinement, hydrogen atom-parent atom vectors were held fixed (riding motion constraint). High-resolution Xray diffraction (HRXRD) measurements were performed at room temperature on an XRD diffractometer (PANalytical's X'Pert PRO) with triple-axis configuration using monochromatized Cu K α radiation (1.5418 Å). To compare the line shape of $2\theta - \omega$ coupled scans and rocking curves, peak intensities were normalized, and the peak positions were centered at zero.

Surface Analysis. The morphology of the hybrid samples was investigated by using scanning electron microscopy (SEM) (JEOL, Model JSM-6480) equipped with X-ray energy-dispersive spectrometry (EDX). EDX spectra were obtained with a beam energy of 10 keV. X-ray photoelectron spectroscopy (XPS) (Thermo Scientific ESCALAB XI+) was performed using 200- μ m-diameter monochromatized Al source ($h\nu = 1486.6$ eV). For depth profiling, sample surface was

repeatedly sputtered with an argon beam (3000 eV, 500 μ m diameter) and analyzed by XPS. The etch rate was estimated to be 10 nm/s. Binding energies were calibrated, relative to the C 1s peak at 284.8 eV.

Thermal Study. Temperature-dependent Raman measurements were performed with a heating system (Linkam, Model TS1500). At each temperature step, 5 min were allowed for thermal stabilization of the sample before Raman spectrum was measured. A 10 °C/min ramping rate was used to heat the sample to the next temperature step. N_2 -protected conditions were achieved by a mild sustained N_2 flow into the chamber during the entire temperature profile.⁵¹ Thermal degradation results shown in Figure S5 in the Supporting Information were obtained in the same way under the N₂ condition with a ramping rate of 20 °C/min to reach the targeted temperature and by taking a Raman spectrum every 5 min. Thermogravimetric analysis was performed using a Mettler-Toledo Model TGA/SDTA851 instrument (Mettler-Toledo AG Analytical, Schwersenbach, Switzerland) in both air and N₂ surroundings. Blanks were run under identical conditions for each gas and subtracted from the respective TGA curves to correct for buoyancy. The ramping rate was 5 °C/min.

Density-Functional Theory Modeling. Density functional theory (DFT) calculations were performed using the Vienna *ab initio* simulation package (VASP).⁵² The projector-augmented wave potentials were used to describe the interaction between the ion cores and valence electrons. The PBEsol generalized gradient approximation was used for the exchange–correlation functional. Plane waves with a cutoff energy of 50 Ry were used as a basis set. The formation energy of β -ZnTe(en)_{0.5} was calculated by taking the total energy difference between bulk β -ZnTe(en)_{0.5} and the sum of zincblende ZnTe and C₂N₂H₈ molecule in the corresponding stoichiometry. ZnTe was calculated in a cubic supercell with an edge length of 15 Å. The accuracy of the formation energy calculation is ~10%.⁵³ Raman spectrum calculations (frequency and symmetry) were performed following ref 54.

ASSOCIATED CONTENT

Supporting Information

This paper has been submitted to a preprint server: Ye, T.; Kocherga, M.; Sun, Y.-Y.; Nesmelov, A.; Zhang, F.; Huang, X.-Y.; Li, J.; Beasock, D.; Jones, D. S.; Schmedake, T. A.; Zhang, Y. Highly Ordered II–VI Based Organic–Inorganic Hybrids with Over 15-Year Shelf Life. arXiv.org, **2020**, arXiv:2006.00349v (URL: https://arxiv.org/abs/2006.00349, submitted on May 30, 2020). The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.1c03219.

EDX and atomic ratio analysis; XPS spectra at different etching times or depths in an extended spectral range; *in situ* heating studies using Raman spectroscopy for a freshly made sample S19-p in air and N₂ at more temperature points; analyses of TGA curves for S19-p in air and N₂; estimation of activation energy (E_A) of thermal degradation by monitoring the intensity decay of the 133 cm⁻¹ Raman mode of the hybrid structure at different elevated temperatures; observed Raman mode frequencies and the corresponding calculated phonon mode frequencies and their symmetry assignments; powder diffraction analyses of S19-p and an optically degraded sample (S06-d); measured and simulated relative intensities for XRD (0,*n*,0) reflection peaks (PDF)

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Notes

The authors declare no competing financial interest.

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