High-K dielectric sulfur-selenium alloys

Sandhya Susarla¹, Thierry Tsafack¹, Peter Samora Owuor¹, Anand B. Puthirath¹, Jordan A. Hachtel², Ganguli Babu¹, Amey Apte¹, BenMaan I. Jawdat¹, Martin S. Hilario³, Albert Lerma⁴, Hector A. Calderon⁶, Francisco C. Robles Hernandez⁶, David W. Tam⁷, Tong Li⁸, Andrew R. Lupini⁹, Juan Carlos Idrobo⁵, Jun Lou¹, Bingqing Wei⁶, Pengcheng Dai⁷, Chandra Sekhar Tiwary¹⁶,¹⁰, Pulickle M. Ajayan¹*

Upcoming advancements in flexible technology require mechanically compliant dielectric materials. Current dielectrics have either high dielectric constant, K (e.g., metal oxides) or good flexibility (e.g., polymers). Here, we achieve a golden mean of these properties and obtain a lightweight, viscoelastic, high-K dielectric material by combining two nonpolar, brittle constituents, namely, sulfur (S) and selenium (Se). This S- Se alloy retains polymer-like mechanical flexibility along with a dielectric strength (40 kV/mm) and a high dielectric constant (K = 74 at 1 MHz) similar to those of established metal oxides. Our theoretical model suggests that the principal reason is the strong dipole moment generated due to the unique structural orientation between S and Se atoms. The S-Se alloys can bridge the chasm between mechanically soft and high-K dielectric materials toward several flexible device applications.

INTRODUCTION

Dielectric materials in the form of insulators, capacitors, and resonators are important passive components in most electrical and electronic circuits used for energy storage, pulsed power, power conditioning, band-pass filtering, sensing, and microelectronics (1–6). The current “flexible” technology wave in these areas (5, 7–10) has increased the demand for flexible high-K dielectric materials (11, 12). Conventional dielectrics are either ceramics or polymers (3, 8, 12–15). Ceramic dielectrics are high-K brittle materials such as BaTiO₃, HfO₂, SiO₂, and SrTiO₃ with large losses and low breakdown voltage (3, 13), whereas polymers such as polyvinylidene difluoride (PVDF), polyamide, and rubber have high dielectric strength and flexibility but low-K values limit their application in devices (8, 12–15). To get the best of both polymer and ceramic dielectrics, polymer composites with various high-K ceramic nanoparticle fillers have been considered (16, 17). We eschew the composite approach in this work to develop a new monolithic, lightweight, flexible, and high-K dielectric material by combining two common nonpolar, brittle constituents, sulfur (S) and selenium (Se), through a facile scalable comelting process. S and Se are miscible in all ratios and form chalcogenide alloys whose optical and photoconduction properties have been studied in the literature (18, 19). The comelted S-Se alloy exhibits viscoelastic behavior and mechanical flexibility like soft polymers. The dielectric constant (K = 74 at 1 MHz) and the dielectric strength (40 kV/mm) are comparable to some of the conventional metal oxides (0 < K < 80) and 10 times higher than polymers (1 < K < 10). There is a 13 times increment in the dielectric constant as compared to the individual components S and Se. Theoretical models suggest that such polarization in S-Se is the result of a strong dipole moment generated because of the unique structural and electronic interactions between S and Se. These chalcogen alloys could fill the gap for soft high-K dielectric materials in several flexible device applications.

RESULTS

Pure S and Se powders were mixed in a mortar and pestle in equimolar ratios (Materials and Methods) and comelted at 573 K in an Ar atmosphere (Fig. 1, A to C). Pure S shows the presence of three Raman peaks corresponding to 152, 218, and 471 cm⁻¹ S-S phonon vibrations. On the other hand, pure Se shows the presence of two phonon modes at 145 and 234 cm⁻¹, attributing to Se-Se bond vibrations. The Raman spectrum of the S-Se alloy in Fig. 1D shows the presence of two peaks attributed to S-Se bonds (255 and 351 cm⁻¹) apart from Se-Se phonon vibrations (239 cm⁻¹). The formation of the S-Se alloy causes a small shift in Se-Se phonon modes (20). X-ray diffraction (XRD) results shown in Fig. 1E indicate that the S-Se alloy adopts a monoclinic structure, with the planes marked with blue ink. The additional peaks, indicated by black ink in Fig. 1E, correspond to residual hexagonal Se (DB: 04-008-1850; DB: 04-003-6030). The detailed indexing of all the XRD peaks is described in table S1. The large background signal in XRD data indicates that the comelted alloy is semicrystalline in nature. XRD of pure S and Se reveals that they adopt a monoclinic and hexagonal structure, respectively (fig. S1). Thermogravimetric analysis (TGA) shows that the alloy’s thermal stability lies between pure S and Se. S and Se degrade at 488 and 623 K, respectively, while the alloy degrades at 573 K (Fig. 1F). The layer-type morphology of the alloys was observed under a scanning electron microscope (SEM) (Fig. 1G). The absence of voids in the SEM images indicates that the material is dense and nonporous. Optical and SEM images of other concentrations and pure S and Se are discussed in figs. S2 and S4. The elemental composition of the S-Se alloys was confirmed by x-ray photoelectron spectroscopy (XPS). Figure 1H shows four peaks in S 2p region in alloys corresponding to spin states of Se 3Pₓ/₂, 3Pᵧ/₂, S 3Pₓ/₂, and S 2Pᵧ/₂. The spin-split peak of S 2p in the alloy region shifts to the lower energy due to the presence of Se, indicating the development of negative charge over S. In a similar fashion, Se 3d peaks of the alloy shift toward the higher energy side in the presence of S, indicating the development of

¹Department of Materials Science and Nano-engineering, Rice University, Houston, TX 77005, USA. ²Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA. ³Air Force Research Laboratory, Kirtland Air Force Base, Albuquerque, NM 87117, USA. ⁴Leidos Inc., Albuquerque, NM 87106, USA. ⁵Mechanical Engineering Technology, University of Houston, Houston, TX 77204, USA. ⁶Instituto Politécnico Nacional, ESTEM, UPALM, Zacatecano, Mexico CDMX 07338, Mexico. ⁷Department of Physics and Astronomy, Rice University, Houston, TX 77005, USA. ⁸Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA. ⁹Department of Mechanical Engineering, University of Delaware, Newark, DE 19716, USA. ¹⁰Materials Science and Engineering Department, Indian Institute of Technology, Kharagpur-721302, India.
*Corresponding author. Email: cst.iisc@gmail.com (C.S.T.); ajayan@rice.edu (P.M.A.)

positive charge over Se (21). Details about the calculation of composition of alloys from XPS are mentioned in table S2. The composition of the alloy is further characterized through electron energy-loss spectroscopy (EELS), which exhibits both the Se M-edge at 57 eV and the S L-edge at 165 eV, shown in fig. S6. The structural information of the S-Se alloy was also determined at the micro- and nanoscale using selected-area electron diffraction, nanodiffraction, and high-resolution transmission electron microscopy (HRTEM) (details are discussed in figs. S7 to S10).

The molecular arrangement of S-Se was further probed by ab initio calculation. Unlike S that has been extensively studied and shown to exist in a variety of allotropes, $S_n$ with $n > 30$, the allotropy of Se has so far shown only a few selected ones in the solid phase, $Se_m$ with $m$ being 8 or 6 (making $Se_m$ an eight- or six-member ring), or a large number, making $Se_n$ effectively an arrangement of infinite Se chains (22). However, at the synthesis temperature of 573 K, octaselenium ($Se_8$) and octasulfur ($S_8$) appear to be the most abundant and the most stable of their respective allotropes (22, 23). They both adopt a crown conformation with D4h point group symmetry, with Se-Se bond length being roughly 1.14 times the S-S bond length. To derive the geometry of the Se-S monomer that constitutes the building block of the polymeric structure, we analyzed adjacent (Fig. 2A), layered (Fig. 2B), and transverse (Fig. 2C) orientations in terms of formation energy ($\Delta H$), HOMO-LUMO energy ($\Delta E_{\text{HOMO-LUMO}}$), net dipole moment ($\mu$), equilibrium constant ($K$), infrared ($\nu_{\text{IR}}$), and Raman ($\nu_{\text{Raman}}$) frequencies corresponding to the highest peaks. Discussion on each parameter is shown in table S3. The transverse orientation of $S_8$ and $Se_8$ (Fig. 2C) displays the highest polarity ($\mu = 2.8135$ D) as well as very high IR (374.105 cm$^{-1}$) and Raman (374.105 cm$^{-1}$) frequencies at the highest peaks. This signals the presence of both strong and weak bonds between the two molecules. The addition of the good attraction ($\Delta H = -1.031$ eV) to the high stability ($\Delta E_{\text{HOMO-LUMO}} = 3.124$ eV) of the orientation makes it the likeliest orientation in the polymer unit. The orbital mixing diagram in Fig. 2E shows good HOMO-1, HOMO, LUMO, and LUMO+1 $Se_8S_8$ orbitals resulting from the overlap between $Se_8$ and $S_8$ HOMO/LUMO and LUMO/HOMO orbital interactions. Figure 2 (F and G) shows the entire IR and Raman spectra of $Se_8S_8$. The close matching of theoretical Raman peaks with the experimental data (Fig. 1D) confirms the existence of transverse orientation of S and Se in alloy. In the insets, the displacement vectors (blue arrows) at the four S atoms closer to $Se_8$ indicate that those atoms contribute chiefly to the vibrational bending modes of the entire structure, with the closest S atom to $Se_8$ being the major contributor. The orange arrow going through $Se_8$ from the S atom with the longest displacement vector is an $Se_8S_8$ dipole moment, indicating a strong polarization (see fig. S11 for further evidence) from $S_8$ (mostly negatively charged) to $Se_8$ (mostly positively charged), in agreement with the XPS results (Fig. 1H). The existence of Se-Se phonon vibrations in experimental Raman spectra (Fig. 1D) indicates that a
combination of two identical transverse orientations between Se$_8$ and S$_8$, as depicted in Fig. 2D displaying a layered orientation between Se$_8$ and S$_8$, Se$_8$S$_8$, HOMO-1, HOMO, LUMO, and LUMO+1 orbitals shown in the middle. Calculated IR spectrum (F) and Raman spectrum (G) for Se$_8$Se$_8$. The inset shows the displacement vectors (blue arrow on the four closest S atoms to Se$_8$) and dipole moment (orange arrow).

Fig. 2. Ab initio calculations done on S-Se alloys. Examples of adjacent (A), layered (B), and transverse (C) orientations for S$_8$Se$_8$, S$_8$Se$_8$, and Se$_8$Se. (D) Plausible polymer unit for the material. (E) HOMO-LUMO/LUMO-HOMO orbital mixing diagram between Se$_8$ and S$_8$, Se$_8$S$_8$, HOMO-1, HOMO, LUMO, and LUMO+1 orbitals shown in the middle. Calculated IR spectrum (F) and Raman spectrum (G) for Se$_8$Se$_8$. The inset shows the displacement vectors (blue arrow on the four closest S atoms to Se$_8$) and dipole moment (orange arrow).

The possibility of resistance to compression due to transverse arrangement was experimentally verified by conducting compression tests on pure S, pure Se, and S-Se alloys. Snapshots from the compression tests conducted on pure S and Se show that they fracture easily upon application of load and display brittle behavior (Fig. 3, A and C). On the other hand, when the load is applied on the S-Se alloy, instead of fracturing, it undergoes high-strain deformation to a thin sheet. The corresponding stress-strain curves show that the alloys sustain stresses as high as 0.4 GPa (fig. S13A). The load-displacement and stress-strain curves resemble those of elastomeric materials. To quantify the amount of mechanical recovery, we measured the height of the sample during the experiment. It is observed that the alloy recovers 40% strain immediately after the release of load and 96% strain after 10 min (Fig. 3E). Furthermore, cyclic tensile tests were done using dynamic mechanical analysis (DMA) to identify the type of elastic behavior (Fig. 3G). The hysteresis (red shaded portion) in the cyclic loading-unloading curve in the tensile test confirms the viscoelastic behavior of the alloy (24). Next, temperature-dependent (−20° to 60°C) DMA cyclic tensile tests were done on the S-Se material to determine its dynamic modulus, storage modulus, loss modulus, and damping effects (tanθ) (Fig. 3H). At room temperature (25°C), the storage, loss, and dynamic modulus were 150, 80, and 170 MPa, respectively. The glass transition temperature (T$_g$) of the alloy measured from differential scanning calorimetry is 10°C ± 1°C (fig. S13B). The T$_g$ measured here is in agreement with the previous report on S-Se systems (25) and suggests that the synthesized semicrystalline material behaves elastically at room temperature (above the glass transition temperature of the amorphous phase in the material). The stiffness of the alloy as determined by DMA increases at low loading cycles but decreases as the cycle number increases (fig. S13C). The local elastic modulus of the alloy was mapped by atomic force microscopy (AFM) and shows that it has an average stiffness of 3 GPa (Fig. 3F).

As seen earlier from ab initio calculations, a significant chemical affinity exists between S$_8$ and Se$_8$ in the perpendicular orientation. Both molecules are individually nonpolar, but when brought together perpendicularly, a charge delocalization from the most electronegative elements (S) to the others (Se) generates a significant dipole moment between the two molecules (+2.81 D) (Fig. 4A). The existence of a dipole moment in S-Se was experimentally verified by measuring the complex impedance in the Autolab 302 electrochemical workstation using the module FRA32M. The dielectric constant of the S-Se alloy was estimated by calculating the capacitance of the material obtained in the impedance measurement. For this purpose, 10 nm of Au was coated on the top and bottom surfaces and the impedance measurement was carried out. More details on the calculation of the dielectric constant are discussed in Materials and Methods. Figure 4B shows the variation of complex impedance (Z*) and phase (θ) as functions of the frequency at a bias of 0 V and a signal amplitude of 10 mV. The presence of a perfect semicircle in the Nyquist plots (Fig. 4C) confirms the capacitive behavior in the alloys. To determine the capacitance of S-Se to calculate the dielectric constant, we fitted the Nyquist curves to ideal parallel resistor and capacitor equivalent circuit. Details about the calculation of the dielectric constant are described in Supplementary Materials and Methods. The calculated dielectric constant and loss factor as a function of frequency are shown in Fig. 4 (D and E). The large dielectric constant (K) and high loss factor at low frequencies (1 Hz to 1 kHz) are attributed to Maxwell-Wagner-Sillars interfacial polarization effects. Hence, the measurement in this range has not been taken as a genuine dielectric constant value (Fig. 4D) (26). K immediately drops to 74 at 1 kHz and stays at 74 from kilohertz to megahertz frequencies. The large and stable value of the dielectric constant from 1 kHz to 1 MHz indicates the presence of strong dipolar interactions as predicted by ab initio calculations (Fig. 4, A and D, inset). The impedance measurement of the alloy was repeated with alloys of different thicknesses to ensure the consistency in the measurement of the dielectric constant value. The dielectric constant at kilohertz to megahertz frequencies is similar for samples with different thicknesses (fig. S14A and table S4). At higher frequencies (100 GHz), the response time of the dipoles to the electromagnetic field becomes much less than the oscillation of the field and the dielectric constant drops to 4.5 (fig. S14B). The material’s inherent dissipation of electromagnetic energy, i.e., dielectric loss, is determined...
by the imaginary part of the dielectric constant. The dielectric loss was calculated by the phase difference in the impedance at various frequencies (Fig. 4B). The remarkable dielectric stability of the S-Se alloys at kilohertz to megahertz frequencies is evidenced by the low values of loss tangent (0.001), unlike other conventional ceramics such as HfO2 and TiO2 (Fig. 4E) (3, 13). At higher frequencies (100 Hz), the dielectric loss (0.8) is significant as compared to other polymer materials in this frequency range, which may lead to applicability as an absorber at higher frequencies (for example, in the damping of unwanted higher-order resonances in devices) (Fig. S14C) (27). At higher bias (1 V), the capacitance of the alloy is reduced. This occurs because of the change in the shape of the alloy upon application of electrical potential, a common phenomenon for dielectric elastomers (Fig. S14D). It is interesting to note that pure S and Se are nonpolar with dielectric constants of 3 and 6, respectively (fig. S14, E and F). There is a 13 times increase in the dielectric constant when S and Se are combined. It is evident that at a frequency of 1 MHz, among common polymer dielectric materials such as Polypropylene (PP), Polystyrene (PS), and PolyVinylidene Fluoride (PVDF) (0 < K < 10), the S-Se alloy has comparable flexibility and an eightfold increase in the dielectric constant. On the other hand, among the common metal oxides used in the capacitor and semiconductor industries such as HfO2, Ta2O5, Al2O3, and SiO2, this material has a comparable dielectric constant (0 < K < 80) with added flexibility. Thus, the obtained S-Se alloys have polymer-like flexibility and a dielectric constant comparable to that of ceramic metal oxides. The dielectric strength of the S-Se alloy was determined by inserting the samples between two electrodes that had an approximate radius of 4 mm and an electrode gap spacing of 1 mm, with a high-voltage power supply (HVPS) connected to the electrodes. The measured dielectric strength of the alloy (40 kV/mm) is comparable to that of the common polymer dielectric materials such as PP, PS, and PVDF (0 < dielectric strength < 60 kV/mm) (fig. S15) (28).

**DISCUSSION**

In summary, it is observed that surprisingly when two brittle and nonpolar chalcogen elements, S and Se, are comelted, a semicrystalline material is formed, with amorphous S-Se, monoclinic S-Se, and hexagonal Se phases. The local interaction of Se8 and S8 rings in the structure results in high polarization between S8 and Se8 and high resistance to mechanical compression due to repulsion of dipole moments between Se8 and Se8. This molecular-level repulsion in Se-Se bonds in S-Se alloys results in unique mechanical behavior including viscoelasticity with excellent mechanical recovery (96%), high Young’s modulus among polymers (3 GPa), and Tg (9.83 ± 1.14)°C, which is below the room temperature. The polar nature of the alloy results in a high dielectric constant (K = 74) at 1-MHz frequency with an extremely low dielectric loss (0.001). The dielectric strength of this alloy, 40 kV/mm, is quite high among polymer materials. This cheap, scalable, lightweight, elastic, high-K dielectric could become a valuable new dielectric material, with dielectric constant comparable to that of the high-K brittle ceramic metal oxides used in the industry and flexibility comparable to that of...
the low-K polymer dielectrics that are considered for emerging flexible technologies.

MATERIALS AND METHODS
Sample preparation
Commercial S (99.99%; Sigma-Aldrich) and Se (99.99%; Sigma-Aldrich) were taken in equimolar ratios and mixed together in a mortar and pestle. The obtained powder was placed in an alumina boat and comelted in the furnace at a temperature of 573 K for 30 min in an Ar atmosphere. After the sample was cooled, it was taken out of the alumina mold. Another concentration of the alloys (1:1 by weight) was also prepared in the same way except for change in the initial ratio of S and Se.

Sample preparation for mechanical properties
The as-synthesized product was cut into cubes (8.67 mm × 8.67 mm × 4.25 mm) with a sharp blade. The samples were also polished slightly to ensure a flat surface for mechanical testing.

Sample preparation for in situ pressure testing
The sample for pressure was formed by casting the melt of S and Se at 513.15 K in a 1-mm-diameter stainless steel mold and was taken out of the mold by a punch.

Electrochemical properties of S/Se electrode
Li-S/Se batteries were constructed using standard 2032 coin cells, with S/Se films pressed on carbon paper. The cells were fabricated using the above electrode as the working electrode and lithium metal as the counter and reference electrode. The electrolyte that consisted of 1 M LiTFSI and lithium nitrate (0.5 M, LiNO₃) in tetraethylene glycol dimethyl ether (TEGDME) solvent and Celgard as a separator was used. Charge-discharge currents and specific capacities were calculated on the basis of the theoretical capacity composite electrode.

Sample preparation for impedance spectroscopy
Samples (4.00 mm × 4.900 mm × 0.374 mm) were used for measuring dielectric properties using impedance spectroscopy. As-cast samples were recasted as thin films on the Al foil, and samples of the given dimensions were cut with a blade out of the cast. Au (10 nm) was sputtered on both sides of the samples. The Au-coated samples were placed in stainless steel load cell, and impedance was measured at 0-V bias in a frequency range of 1 Hz to 1 MHz. For higher-frequency measurements (100 GHz) and dielectric strength measurements, samples (2 mm × 0.6 mm) were prepared by melting them in the corresponding Al mold.

Sample preparation for electron microscopy
Samples for TEM/scanning TEM (STEM) analysis were prepared by dispersing 1 mg of the S-Se alloy in 20 ml of ethanol solution and ultrasonating it for 10 min.

Electron diffraction indexing
The selected area diffraction (SAD) patterns were calibrated using a gold standard. The d-spacings of the calibrated diffraction patterns were obtained using the Bragg’s law. The d-spacing of the polycrystalline rings is indicated in table S1. Calibrated nanodiffraction data were also indexed in the same way as the SAD pattern.

Characterization
All the Raman spectroscopy measurements were carried out with a Renishaw inVia microscope using a 532-nm laser at a power of 60.4 μW. The data were analyzed using Wire 3.3 software. XRD measurements were done using Rigaku D/Max Ultima II with Cu Kα radiation. The XRD data were analyzed using an integrated powder XRD analysis.
XPS measurement was carried out with PHI Quantera XPS using Al Kα radiation operated at 200 eV. The data analysis was done using MultiPak software. The composition of the alloys was determined by calculating the area under the peak for individual spin-split S 2p and Se 3d pairs. The overlapping Se 3p3/2 of the alloys was determined by calculating the area under the peak for the band-gap measurement reported here, only the first five frames extracted.

Stiffness of the alloy was done on a DMA Q800 instrument (TA Instruments, USA). The test was conducted in a compression mode at ambient conditions with a 1-Hz cycle in a controlled strain rate mode. The mapping of mechanical stiffness was performed with AFM. The experiments were carried out with MultiMode AFM (Bruker, MA). An RTESP probe (Bruker, MA) with a resonance frequency of 530 kHz was used to map an area of 5 μm × 5 μm. The indentation depth was defined as 200 nm, and the scanning rate was 0.5 Hz. A Hertz contact model, provided in the NanoScope Analysis software (V140r1, Bruker, MA), was used to calculate the Young’s modulus for each scanning point (512 × 512). Gwyddion software (29) was used to plot the three-dimensional profile of mechanical stiffness. The dielectric constant measurements were carried out with an Autolab 302 electrochemical workstation using a FRA32M module under 0-V bias and 10-mV signal amplitude. The ideal RC parallel equivalent circuit model was used to estimate the capacitance of the alloy. The circuit diagram used for calculations is shown in fig. S19. In a typical RC circuit model, the characteristic relaxation time or time constant, of each parallel RC element τ is given by the product of R and C

$$\tau = RC$$

and

$$\omega_{max}RC = 1$$

Impedance data were presented in the form of imaginary Z″ (capacitive) against real Z' (resistive). Each parallel RC element gave rise to a semicircle (ideally) from which the component R and C values may be extracted. R values were obtained from the intercepts on the Z' axis, and C values were obtained by applying the equation above to the frequency at the maximum of each semicircle. Because of the obtained values for these R and C components, for a parallel plate capacitor with area A, separation l between the plates, and a medium of permittivity ε′ between the plates, the capacitance is given by

$$C = \frac{\varepsilon_0 \varepsilon_i A}{d}$$

where A is the area of electrodes, d is the separation between the electrodes, ε0 is the permittivity of free space (8.85 × 10⁻¹² F/m), and εi is the dielectric constant of the material.

Thus, the dielectric constant values were deduced (30).
**In situ pressure setup**
For the application of uniaxial pressure, we used an instrument with a linear thruster and load cell in a feedback loop (31). The linear thruster was operated using compressed air, with a voltage-controlled regulator and a bleed valve controlling the inlet pressure. Mechanical force was transferred to the sample by means of concentric stainless steel tubes, with the outer tube holding an aluminum frame that supports the sample and the inner tube applying compressive force onto the sample relative. The load cell is in series with the inner tube, and the feedback loop is closed in the LabVIEW software. We mounted the apparatus horizontally with the sample positioned in the Raman laser. Pressure on the sample was estimated by measuring the transverse size of the sample. In the uniaxial pressure instrument, the S-Se sample continuously deformed over the course of several minutes at pressures as low as 1 MPa. The Raman scans were taken during the compression phase, and the sample completely expanded back to its original shape before the next pressure was applied.

**Dielectric constant measurement at higher frequencies**
In the dielectric measurement setup, an Agilent PNA 5222A vector network analyzer provided a low-power beam, which was boosted into the W-band (75–110 GHz) by a pair of frequency extenders. This beam was focused onto a small 0.67-inch spot by a pair of Gaussian lenses. To calculate the dielectric properties, the S parameters were first obtained by measuring the reflection and transmission coefficients. Once the S parameters were known as a function of frequency, fits were made to the data to obtain the real and imaginary parts of the dielectric constant.

**Dielectric breakdown setup**
The S-Se samples were tested in a high-density polyethylene dielectric holder with electrodes that had an approximate radius of 4 mm and an electrode gap spacing of the sample thickness, which was about 1 mm. One electrode was spring-loaded for retention of the sample, and the other electrode was stationary. The negative output of the HVPS was connected to the stationary electrode, while the grounded return of the HVPS was connected to the spring-loaded electrode. A Northstar (VD-120) high-voltage probe (10,000:1) was also connected to the stationary electrode to observe the breakdown voltage on a LeCroy oscilloscope. The sample was placed between the electrodes and submerged in Dila AX for testing. The ramp rate was 3 kV/s.

**Electrochemical properties**
Electrochemical properties such as cyclic voltammograms and charge-discharge studies were measured in the potential range from 1.7 to 2.8 V using an Autolab electrochemical workstation and an ARBIN cycle life tester, respectively.

**Computational details**
The structures for $S_8-S_8$, $S_8-Se_8$, $Se_8-Se_8$, and $S_8-S_4Se_4$ in adjacent (Fig. 2A), layered (Fig. 2B), and transverse (Fig. 2C) configurations were constructed in the advanced semantic chemical editor and visualization platform, Avogadro 1.2.0 (32). The structures were then optimized using the all-electron density functional theory equations implemented in the Gaussian 09 package with the B3LYP functional of generalized gradient approximation and the 6-31G basis set (33, 34). The threshold convergence criteria for the root mean square (RMS) force, maximum displacement of atoms, maximum force, and RMS displacement were set to 0.0003, 0.0018, 0.00045, and 0.0012 a.u. (atomic units), respectively. Regarding the reactions in table S3, the energy difference between products and reactants ($\Delta H$) as well as the HOMO-LUMO energy differences ($\Delta(E_{\text{HOMO-LUMO}})$) and molecule net dipole moments (\(\mu\)) were calculated. The equilibrium constant, $K = e^{-\Delta H/kT}$ (where $R$ is the ideal gas constant, $\sim 0.802$ eV/K), was also calculated at the synthesis temperature of 513.15 K. IR and Raman spectra at different frequencies were calculated during the optimization process, and the frequencies corresponding to the highest peaks are shown in table S3.

**REFERENCES AND NOTES**


Acknowledgments: We thank S. Sajadi for help in making mechanical testing videos and H. Gullapalli for technical advice. We also thank B. Hoff for technical expertise on dielectric constant measurement and S. Heidger for advice on dielectric breakdown measurement. We also thank P. Bharadwaj for inputs on ultraviolet-visible spectroscopy measurements. Funding: This work was supported as part of the Computational Materials Sciences Program funded by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES) under award number DE-SC00014607. We thank the Science & Engineering Research Board (SERB) and Indo-US Science and Technology Forum (IU STF) for financial support in the form of postdoctoral fellowship. Microscopy research was performed as part of a user proposal at ORNL’s Center for Nanophase Materials Sciences (CNMS), which is a U.S. DOE, Office of Science User Facility at the ORNL. The research was supported by the Materials Sciences and Engineering Division Office of BES, U.S. DOE and conducted, in part, using instrumentation within ORNL’s Materials Characterization Core provided by UT-Battelle LLC under contract no. DE-AC05-00OR22725 with the U.S. DOE. The in situ pressure experiments on the Raman microscope were supported by the U.S. DOE, BES (award number DE-SC0012311) and the Robert A. Welch Foundation (grant C-1839) (to P.D.). Author contributions: S.S. wrote the major part of the paper, synthesized the material, and carried out XRD, XPS, SAED, Raman, and impedance spectroscopy measurements. T.T. performed the molecular dynamics simulations. P.S.O. and J.L. conducted the compression, DMA, and TGA tests. A.A. helped in the sample preparation for the impedance testing. G.B. and A.B.P. did the impedance measurements and Lithium battery testing. T.L. and B.W. mapped the AFM modulus of the 5-Se alloys. D.W.T. and P.D. designed the in situ pressure system for Raman measurements. B.L.J. and M.S.H. carried out the dielectric constant measurements at higher frequencies. A.L. carried out the dielectric breakdown measurement. J.A.H. carried out the nanodiffraction and EELS measurements. J.C.L. and A.R.L. advised on the nanodiffraction measurements. H.A.C. and F.C.R.H. performed HRTEM measurements on the sample. C.S.T. and P.M.A. supervised the project. All authors participated in discussions and contributed to writing the manuscript. Competing interests: This manuscript has been authored by UT-Battelle LLC under contract no. DE-AC05-00OR22725 with the U.S. DOE. The U.S. government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. government purposes. The DOE will provide public access of these results for federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan). T.T., P.S.O., S.S., P.M.A., A.B.P., and C.S.T. are inventors on a provisional patent application related to this work filed by Rice University (no. 62/713,375, filed on 1 August 2018). Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. The 5-Se alloy can be provided by authors pending scientific review and a completed material transfer agreement. Requests for the materials should be submitted to the Office of Technology Transfer, Rice University, 6100 Main Street, Houston, TX 77005-1892, USA.

Submitted 2 August 2018
Accepted 29 March 2019
Published 10 May 2019
10.1126/sciadv.aau9785

High-K dielectric sulfur-selenium alloys


DOI: 10.1126/sciadv.aau9785

Use of this article is subject to the Terms of Service