Universal conductance fluctuations and phase-coherent transport in a semiconductor Bi$_2$O$_2$Se nanoplate with strong spin-orbit interaction

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We report on phase-coherent transport studies of a Bi$_2$O$_2$Se nanoplate and on observation of universal conductance fluctuations and spin-orbit interaction induced reduction in fluctuation amplitude in the nanoplate. Thin-layered Bi$_2$O$_2$Se nanoplates are grown by chemical vapor deposition (CVD) and transport measurements are made on a Hall-bar device fabricated from a CVD-grown nanoplate. The measurements show weak antilocalization at low magnetic fields at low temperatures, as a result of spin-orbit interaction, and a crossover toward weak localization with increasing temperature. Temperature dependences of characteristic transport lengths, such as spin relaxation length, phase coherence length, and mean free path, are extracted from the low-field measurement data. Universal conductance fluctuations are visible in the low-temperature magnetoconductance over a large range of magnetic fields and the phase coherence length extracted from the autocorrelation function is in consistence with the result obtained from the weak localization analysis. More importantly, we find a strong reduction in amplitude of the universal conductance fluctuations and show that the results agree with the analysis assuming strong spin-orbit interaction in the Bi$_2$O$_2$Se nanoplate.

Keywords: Bi$_2$O$_2$Se, nanoplate, universal conductance fluctuations, spin-orbit interaction

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Since the discovery of graphene, extensive research has been focused on realizations of various two-dimensional (2D) materials systems and on their potential applications in electronics, optoelectronics, and nanoelectromechanical systems. Recently, a new type of 2D materials, semiconductor Bi$_2$O$_2$Se nanoplates, have been successfully synthesized via chemical vapor deposition. These CVD-grown Bi$_2$O$_2$Se nanoplates can be stored in ambient environment for a considerably long period of time without crystal quality degrading. Bi$_2$O$_2$Se has an indirect bandgap of ~0.8 eV and field-effect devices made from non-encapsulated Bi$_2$O$_2$Se nanoplates exhibit high electron mobility of ~450 cm$^2$ V$^{-1}$ s$^{-1}$ at room temperature. Based on their suitable bandgap and high carrier mobility, Bi$_2$O$_2$Se nanoplates have been used to construct infrared photodetectors with fast response and high sensitivity.

Bi$_2$O$_2$Se also exhibits excellent low-temperature transport properties. For example, high electron mobility at low-temperature has been reported in Bi$_2$O$_2$Se layers (~28000 to ~280000 cm$^2$ V$^{-1}$s$^{-1}$) and, as a result, Shubnikov-de Haas (SdH) oscillations have been detected in these materials. Recently, we demonstrated the existence of strong spin-orbit interaction in Bi$_2$O$_2$Se nanoplates and observed weak antilocalization (WAL), a signature of spin-orbit interaction, and its crossover to weak localization (WL) with increasing temperature or decreasing gate voltage. These phase-coherent transport properties make Bi$_2$O$_2$Se nanoplates very interesting for applications in quantum electronics and spintronics, and for exploring new physics. However, no report has been made on observations of universal conductance fluctuations (UCFs) and their amplitude reduction due to spin-orbit interaction, an important signature of phase coherent transport in strong spin-orbit interacting systems, in Bi$_2$O$_2$Se nanoplates.

In this work, we report on a phase-coherent transport study of a Bi$_2$O$_2$Se nanoplate and on observation of UCFs and their amplitude reduction due to spin-orbit interaction in the layered material. Bi$_2$O$_2$Se nanoplates are grown via CVD on a mica substrate and our transport measurements are performed on a Hall-bar device made from a CVD-grown Bi$_2$O$_2$Se nanoplate on a SiO$_2$/Si substrate in a physical properties measurement system (PPMS). Here we note that the device is made from a Bi$_2$O$_2$Se nanoplate with a thickness of ~24 nm, slightly thicker than the nanoplates used previously in Ref. 9, in order to achieve a longer coherence.
length and thus stronger conductance fluctuations at low temperature measurements. In the following, we will first give brief descriptions about the materials growth and device fabrication. We then present the results of transport characterization measurements, in which the characteristic transport parameters, such as coherence length, spin relaxation length, and mean free path, and their temperature dependences in the nanoplates are extracted and discussed. In particular, we will show that a crossover between WAL and WL occurs at \(~10\) K in weak magnetic-field magnetotransport measurements of the nanoplate. After these characterization measurements, we present the main results of this work, namely the observation of UCFs at low temperatures. Here we will show for the first time that UCFs are observed over a large range of magnetic fields in a Bi$_2$O$_2$Se nanoplate at low temperatures and that the amplitude of UCFs is reduced at temperatures below \(~10\) K when compared to the trend deduced from high temperature region. Our analysis shows that the observed amplitude reduction is fully in agreement with the prediction by the theory of Refs. 24 and 25, and can be firmly attributed to spin-orbit interaction effect. Our observation of UCFs and their amplitude reduction in the Bi$_2$O$_2$Se nanoplate would stimulate further experimental and theoretical studies of the systems.

The Bi$_2$O$_2$Se nanoplate studied in this work is grown in a low-pressure CVD system.\(^3\) The source materials are Bi$_2$O$_3$ and Bi$_2$Se$_3$ (Alfa Aesar, 99.995\%) powders, which are placed in a horizontal quartz tube. Fluorophlogopite mica is used as a growth substrate. For further details about the nanoplate growth, we would like to refer to Ref. 3. An optical image of a few CVD-grown Bi$_2$O$_2$Se nanoplates on the mica substrate is shown in Fig. 1(a). Here, the nanoplates seen with different brightnesses are different in thickness. The square shape of the nanoplates results from the Bi$_2$O$_2$Se tetragonal crystal structure.\(^{10}\) Figure 1(b) is an atomic force microscope (AFM) image of a Bi$_2$O$_2$Se nanoplate with ultra-smooth surface. A high resolution transmission electron microscope (TEM) image of a Bi$_2$O$_2$Se nanoplate is shown in Fig. 1(c), confirming its high crystal quality. Figure 1(d) shows the typical spectra of X-ray photoelectron spectroscopy (XPS) measurements of as-grown Bi$_2$O$_2$Se nanoplates, consisting of obvious Se$_{3d}$ and Bi$_{4f}$ peaks. The two peaks of Bi$_{4f}$ located at 158.7 and 164.0 eV (higher than those in Bi$_2$Se$_3$)\(^{11}\) are clearly observed and are attributed to the chemical bonding of
Bi(III)-O\(_x\) in Bi\(_2\)O\(_2\)Se.\(^{12}\) These results reveal the feature of chemical bond states of Bi\(_2\)O\(_2\)Se nanoplates and indicate again the high quality of the prepared 2D crystals.

As-grown Bi\(_2\)O\(_2\)Se nanoplates are transferred from the growth mica substrate to a SiO\(_2\)/Si substrate for device fabrication using PMMA (polymethyl methacrylate)-mediated technique.\(^{12}\) Devices are fabricated from selected Bi\(_2\)O\(_2\)Se nanoplates on the SiO\(_2\)/Si substrate with contact electrodes made with a double layer of Ti/Au (5/70 nm in thickness) in a Hall-bar configuration using standard nanofabrication techniques of electron beam lithography, metal evaporation and lift-off, see Ref. 9 for further details about the device fabrication. The inset of Fig. 2(a) shows an optical image of the fabricated Bi\(_2\)O\(_2\)Se nanoplate device studied in this work. A schematic of the transport measurement circuit setup is shown in the inset of Fig. 2(b).

The device is mounted to a rotatable sample holder and the measurements are performed in a PPMS quipped with a uniaxial magnet with supplied magnetic fields up to 9 T. The longitudinal voltage \(V_x\) and the transverse voltage \(V_y\) are detected simultaneously using standard lock-in technique with a 17 Hz, 100 nA excitation current \(I_{SD}\) applied between the S and D electrodes, see the inset of Fig. 2(b). The longitudinal resistivity \(R\) and the Hall resistance \(R_{yx}\) are obtained as \(R=R_{xx}\times W/L\) and \(R_{yx}=V_y/I_{SD}\), where \(R_{xx}=V_x/I_{SD}\) is the longitudinal resistance, \(L\) is the distance between the two voltage probes along the current direction and \(W\) is the width of the nanoplate. For the device studied in this work, we have \(L=4.2\) µm and \(W=3.8\) µm.

Figure 2(a) shows the measured sheet resistivity \(R\) of the Bi\(_2\)O\(_2\)Se nanoplate device shown in the inset of the figure as a function of temperature \(T\) at zero magnetic field. It is seen that \(R\) monotonically decreases as \(T\) decreases from 300 to 10 K and saturates at \(T\) below \(\sim 10\) K. The Hall measurements show that the Bi\(_2\)O\(_2\)Se nanoplate is electron conductive over the entire range of temperatures measured, which is consistent with the results previously reported.\(^9\) Figure 2(b) shows the Hall electron mobility \(\mu\) and sheet carrier density \(n_{\text{sheet}}\) extracted from the measured \(R\) and \(R_{yx}\) at different temperatures (see Supplemental Materials). The sheet carrier density \(n_{\text{sheet}}\) is seen to decrease with lowering \(T\) from 300 K and tends to saturate when \(T\) goes below \(\sim 10\) K. Mobility \(\mu\) increases as \(T\) decreases and also shows a saturation behavior at \(T\) below \(\sim 10\) K. The temperature evolution characteristics of \(\mu\) and \(n_{\text{sheet}}\) suggest that phonon scattering to the cruising electrons is frozen out below \(\sim 10\) K in the
Bi$_2$O$_2$Se nanoplate.$^{13}$ As shown in Fig. 2(b), at 2 K, $n_{\text{sheet}}$ is $\sim 1.15 \times 10^{13}$ cm$^{-2}$ and $\mu$ reaches $\sim 1466$ cm$^2$/V$\cdot$s, giving an electron mean free path of $l_e \sim 82$ nm, about two orders of magnitude smaller than the length and the width of the Hall-bar device. Thus, the transport in the Bi$_2$O$_2$Se nanoplate device is in the diffusive regime at 2 K.

Figure 3(a) shows the magnetoconductance $\Delta G_{xx}(B) = G_{xx}(B) - G_{xx}(B = 0)$ at 2 K with magnetic field $B$ applied at different tilting angles $\theta$, where $\theta$ is the angle between the field and the transverse in-plane direction as shown in the inset of Fig. 3(b). Here, $G_{xx}(B)$ is the longitudinal conductance obtained from the measured longitudinal resistance $R_{xx}$ and transverse resistance $R_{yx}$ (see the Supplementary Materials for details), and the curves are successively vertically offset from that at $\theta = 90^\circ$ for clarity. It is seen that when the magnetic field is applied perpendicular to the device substrate ($\theta = 90^\circ$), the magnetoconductance shows a sharp peak in the vicinity of zero field, i.e., a signature of WAL, consistent with the presence of strong spin-orbit interaction in the Bi$_2$O$_2$Se nanoplate.$^{9,14}$ When the magnetic field is rotated away from $\theta = 90^\circ$ toward the transverse in-plane direction, the WAL peak becomes broadened. Figure 3(b) depicts the magnetoconductance $\Delta G_{xx}(B)$ against the vertical component of the field, i.e., $B \sin(\theta)$. Here, all the magnetoconductance curves coincide with each other, verifying the 2D nature of transport in the Bi$_2$O$_2$Se nanoplate. The magnetoconductance measurements at low, perpendicular magnetic fields $B$ can be described by quantum interference theory,$^{15}$ which describes the quantum correction to the low-field magnetoconductance in a diffusive 2D system as,$^{15,16}$

$$
\Delta G(B) = -\frac{e^2}{\pi \hbar} \left[ \frac{1}{2} \Psi \left( \frac{B_e}{B} + \frac{1}{2} \right) + \Psi \left( \frac{B_{so} + B_e}{B} + \frac{1}{2} \right) + \frac{3}{2} \Psi \left( \frac{(4/3)B_{so} + B_{\varphi}}{B} + \frac{1}{2} \right) - \frac{1}{2} \ln \left( \frac{B_{\varphi}}{B} \right) \right]
$$

Here, $\Psi(x)$ is the digamma function. $B_i$, with $i = \varphi, \text{SO}$, and $e$, describe the characteristic fields for different scattering processes and are given by $B_i = \hbar/(4eL_i^2)$ with $L_{\varphi}$ being the phase coherence length, $L_{SO}$ the spin relaxation length, and $L_e$ the electron mean free path.

Figure 3(c) shows the low-field magnetoconductance curves of the Bi$_2$O$_2$Se nanoplate device obtained at different temperatures. Here, the curves are successively vertically offset from that at $T = 2$ K for clarity. As the temperature increases from 2 to 12 K, the WAL peak gradually broadens and the magnetoconductance curves eventually develops into a broad dip.
a signature of WL. We fit the experimental data in Fig. 3(c) to Eq. (1) and the results are presented by solid lines in the figure. Figure 3(d) plots the transport characteristic lengths, $L_\phi$, $L_{SO}$ and $L_e$, extracted from the fits against temperature. It is shown that $L_{SO}$ remains constant around ~250 nm, while $L_\phi$ is ~500 nm at 2 K and decreases with increasing temperature as $L_\phi \sim T^{-0.51}$ due to enhanced inelastic scattering at increased temperatures. This power-law temperature dependence is consistent with the 2D nature of transport in the nanoplate and proves that dephasing is dominantly due to electron-electron scattering processes with small energy transfers.\textsuperscript{17} The extracted values of $L_\phi$ and $L_{SO}$ cross at $T$~10 K at which the magnetoconductance shows a crossover between the WAL and WL characteristics. The extracted $L_{SO}$ is longer than the previously reported value (150 nm) in Ref. 9 and thus the spin-orbit coupling strength of the device studied in this work is slightly weakened. This is because spin-orbit interaction is mainly derived from Bi-$p_z$ orbits and their contribution to the conduction band electrons are weakened due to the fact that the Bi$_2$O$_2$Se nanoplate (24 nm in thickness) used in this work is much thicker and the electron Fermi energy ($E_F \sim 19$ meV) is significantly higher, when compared with the values (8 nm and 0.85 meV) in the nanoplate used in the previously reported work.\textsuperscript{9} In addition, the extracted $L_\phi$ and $L_e$ in the present device are also much longer than the corresponding values in the Bi$_2$O$_2$Se nanoplate used in the previous report.\textsuperscript{9}

Figure 4(a) shows the UCFs, $\delta G(B)$, extracted for the nanoplate device at different temperatures. Here, each curve is obtained by subtracting a polynomial background from the magnetoconductance data measured at vertically applied magnetic fields. When temperature increases, the main oscillation features in UCF patterns are reproducible, while the amplitude of the fluctuations gradually reduces due to enhanced inelastic scattering and thermal average. Figure 4(b) shows the measured UCF patterns at different field orientations $\theta$ [cf. the inset of Fig. 3(b)]. Here, the measured data are plotted against the vertical field component, i.e., $B \sin(\theta)$ and it is seen that the fluctuation patterns are solely dependent on the vertical component of the field, demonstrating again the 2D nature of transport in the Bi$_2$O$_2$Se nanoplate.\textsuperscript{18} UCFs are a quantum interference effect and the phase coherence length $L_\phi$ could also be extracted from the autocorrelation function of UCFs, $F(\Delta B) = \langle \delta G(B + \Delta B)\delta G(B) \rangle$,.
where the brackets \( \langle \cdots \rangle \) represents an average over magnetic fields \( B \). For a 2D system, the phase coherence length \( L_{\phi} \) is estimated from \((L_{\phi})^2 \Delta B_c \simeq \Phi_0\), where \( \Phi_0 \) is the flux quantum and \( \Delta B_c \) is the width at half maximum of the autocorrelation function \( F(\Delta B_c) = \frac{1}{2} F(0) \), see Supplementary Materials for further details. Figure 4(c) shows the extracted \( L_{\phi} \) at different temperatures. Here, again, \( L_{\phi} \) decreases with increasing temperature and can be fitted by a power law function of \( T^{-0.46} \). This temperature dependence is close to the result obtained based on WL and WAL analyses as shown in Fig. 3(d) and is consistent with the 2D nature of transport in the nanoplate, indicating that the same mechanism is involved in dephasing. However, we should note that the values of \( L_{\phi} \) extracted from UCFs are overall smaller than that extracted from the WL and WAL analyses. This could be understood as that unlike WL and WAL analyses, which dominantly take into account interference processes between specific, time reversal symmetric, closed paths, UCFs arise from interferences from all possible paths between two points in the Bi₂O₂Se nanoplates.\(^{14,19}\)

In a 2D system with \( L > L_{\phi} \) (as in the case for this work), the average effect among different coherent areas leads to a reduction in amplitude of conductance fluctuations. Considering this large-size average effect and the thermal average effect arising from finite temperatures, the fluctuation amplitude \( \delta G_{\text{rms}} \), where subscript \( \text{rms} \) stands for the root-of-mean-square value, can be described by \( \propto L_T / L \sqrt{\ln(L_{\phi}/L_T)} \), where \( L_T = \sqrt{\hbar D / k_B T} \) is the thermal length, without taking the amplitude reduction due to spin-orbit interaction into account.\(^{20}\) Here, for a 2D system, \( \delta G_{\text{rms}} \propto T^{-1/2} \) would be observed. However, as we will show in the following, spin-orbit interaction leads to a strong reduction in \( \delta G_{\text{rms}} \) in our nanoplate device. Figure 4(d) shows \( \delta G_{\text{rms}} / \langle G \rangle \) as a function of \( 1/\sqrt{T} \). The \( \delta G_{\text{rms}} / \langle G \rangle \) exhibits a linear dependence on \( 1/\sqrt{T} \) in the high temperature region, where \( L_{\phi} \) is shorter than \( L_{SO} \) and thus the effects of spin-orbit interaction on coherence transport phenomena are negligibly small. This \( 1/\sqrt{T} \) dependence is in good agreement with theory of electron-electron scattering induced dephasing in a 2D system.\(^{19}\) The red dashed line in the figure is the
result of extending the linear fit from the high temperature region to the low temperature region. It is clearly seen that at T < 10 K, the measured $\delta G_{rms}/\langle G \rangle$ increases more slowly and deviates away from the $1/\sqrt{T}$ dependence. This phenomenon has been previously observed in GaAs/AlGaAs heterojunctions\textsuperscript{21} and InAs nanowires,\textsuperscript{22} and has been attributed to the presence of strong spin-orbit interaction.\textsuperscript{21,22} In the Bi$_2$O$_2$Se nanoplate studied in this work, $L_{SO}$ becomes shorter than $L_{\varphi}$ at T< 10 K, and strong spin-orbit coupling can thus influence the cruising electrons via introducing an effective magnetic flux which has opposite sign for spin-up and spin-down electrons, resulting in a reduction in amplitude of UCFs.\textsuperscript{23,24} To evaluate the effect of spin-orbital interaction on UCF amplitudes in our nanoplate, we fit our measured data in Fig. 4(d) with a semi-classical result,\textsuperscript{21,23} $\delta G_{rms}/\delta G_{rms}^0 = 0.5\{3 \exp(-4L_e^2/3L_{SO}^2) + 1\}^{1/2}$, where $\delta G_{rms}^0$ denotes the amplitude of UCFs in the system that would have no spin-orbital scattering [represented by the dashed line in Fig. 4(d) for our device], $L_e$ is a characteristic length which is proportional to $L_{\varphi}$. The blue solid line is the fitting result and $L_e = 2.8L_{\varphi}$ is extracted from the fitting. As is shows in Fig. 4(d), $\delta G_{rms}/\langle G \rangle$ at 2 K is reduced to $\sim$75% of the value that would be obtained from the dashed line, i.e., if no spin-orbit coupling is present in the system. Note that in the infinitely strong spin-orbit coupling limit, a reduction factor of 50% in $\delta G_{rms}/\delta G_{rms}^0$ is predicted by the semi-classical theory.\textsuperscript{23} Our observed reduction factor is about half of the value that would be observed in the infinitely strong spin-orbit interaction limit and is significantly larger than the reduction factor value observed previously in conventional GaAs/AlGaAs heterostructures.\textsuperscript{21}

In conclusion, we have studied the phase coherent transport in a Bi$_2$O$_2$Se nanoplate device. The device is made from a Bi$_2$O$_2$Se nanoplate of 24 nm in thickness, thicker than the nanoplate used in the study reported previously in Ref. 9. WAL and UCFs are observed in the magnetotransport measurements and the latter are for the first time reported for a Bi$_2$O$_2$Se nanoplate. The measurements are well described by theory of coherent transport in 2D diffusive systems and characteristic transport lengths, $L_{\varphi}$, $L_{SO}$ and $L_e$, in the Bi$_2$O$_2$Se nanoplate are extracted at different temperatures. It is found that at low temperatures of 2 to 25 K, $L_{SO}$~250 nm and $L_e$~82 nm are insensitive to temperature variations, while $L_{\varphi}$
shows a $T^{-1/2}$ temperature dependence suggesting that dephasing in the nanoplate arises dominantly from electron-electron scattering processes with small energy transfers. Most importantly, we find that the observed UCFs in the nanoplate show a strong reduction in fluctuation amplitude, which is in good agreement with a semi-classical description by taking into account strong spin-orbit scattering in the Bi$_2$O$_2$Se nanoplate. It is expected that our results presented in this work will stimulate exploration of semiconductor Bi$_2$O$_2$Se layers for applications in quantum electronics, spintronics and quantum information technology.

This work is supported by the Ministry of Science and Technology of China through the National Key Research and Development Program of China (Grant Nos. 2017YFA0303304, 2016YFA0300601, 2017YFA0204901, and 2016YFA0300802), and the National Natural Science Foundation of China (Grant Nos. 11874071, 91221202, 91421303, and 11274021). HQX also acknowledges financial support from the Swedish Research Council (VR).
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Fig. 1 (a) Optical image of as-grown Bi$_2$O$_2$Se nanoplates on a mica substrate. Here, a few of square- or rectangle-shaped nanoplates with different thicknesses, as indicated by their brightnesses, are seen. (b) Typical AFM image of a Bi$_2$O$_2$Se nanplate, showing an ultrasmooth surface. (c) High resolution TEM image of a Bi$_2$O$_2$Se nanoplate taken from the c-axis direction. The inset is a low-magnification TEM image of a Bi$_2$O$_2$Se nanplate transferred onto a holey carbon grid. (d) XPS characterization spectra of an as-grown Bi$_2$O$_2$Se nanoplate sample, in which Bi 4f and Se 3d core level photoemission spectra are displayed.
FIG. 2. (a) Measured sheet resistivity $R$ of the Bi$_2$O$_2$Se nanoplate studied in this work as a function of temperature $T$. The inset shows an optical image of the measured Hall-bar device made from the nanoplate. The nanoplate has a thickness 24 nm. (b) Electron mobility ($\mu$) and sheet carrier density ($n_{\text{sheet}}$) extracted for the nanoplate as a function of $T$. The inset shows a structure schematic of the Bi$_2$O$_2$Se nanoplate device and the measurement circuit setup.
FIG. 3. (a) Magnetoconductance $\Delta G_{xx}(B)$ measured at 2 K with the external magnetic field $B$ applied at different orientations $\theta$, see the schematic shown in the inset of (b) for the definition of $\theta$. The red curve displays the measurements at $\theta = 90^\circ$ and all other measurements are successively vertically offset for clarity. (b) Magnetoconductance $\Delta G_{xx}(B)$ plotted against the vertical component $B \sin(\theta)$ of the applied magnetic field $B$. (c) Magnetoconductance $\Delta G_{xx}(B)$ measured for the Bi$_2$O$_2$Se nanoplate device with the magnetic field applied in the vertical direction ($\theta = 90^\circ$) at temperatures of 2 to 12 K. The bottom curve displays the measurement data at 2 K and all other curves are successively vertically offset for clarity. The solid lines are the results of theoretical fits to the experimental data based on Eq. (1). Here, a WAL–WL crossover occurs as temperature increases. (d) Phase coherence length $L_\phi$, spin relaxation length $L_{sO}$, and mean free path $L_e$, extracted from the fittings of the experimental results shown in (c), plotted against temperature $T$. The black solid line is the power-law fit of $L_\phi$, showing $L_\phi \sim T^{-0.51}$. 
FIG. 4. (a) Conductance fluctuations $\delta G$ plotted against vertically applied magnetic field $B$ at different temperatures. Similar aperiodic patterns appear in $\delta G$ at different temperatures. (b) Conductance fluctuations $\delta G$ measured with magnetic field applied in different orientations $\theta$ [cf. the inset of Fig. 3 (b)] as a function of the vertical component of the magnetic field. It can be seen that the conductance fluctuation patterns solely depend on the vertical component of the field. (c) Phase coherence length $L_\phi$ extracted from the autocorrelation function $F(\Delta B)$ of the conductance fluctuations at different temperatures. The solid line is the result of power law fitting, showing that $L_\phi \sim T^{-0.46}$. (d) Normalized root-of-mean-square value of the conductance fluctuations, $\delta G_{rms}/<G>$, plotted against $T^{-1/2}$. The red dashed line represents the result obtained by a line fit to the trend found at high temperatures. The blue solid line is the result of theoretical fit to the measured data as discussed in the text. Deviations of the measured data from the red dashed line at low temperatures arise from reductions in UCF amplitude induced by spin-orbit coupling in the nanoplate.
Supplementary Materials for
Universal conductance fluctuations and phase-coherent transport in the presence of spin-orbit interaction in a semiconductor Bi$_2$O$_2$Se nanoplate

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Contents

Figure S1. Longitudinal resistance $R_{xx}$ of the Bi$_2$O$_2$Se nanoplate vs. vertically applied magnetic field at different temperatures

Figure S2. Transverse resistance $R_{yx}$ of the Bi$_2$O$_2$Se nanoplate vs. vertically applied magnetic field at different temperatures

Figure S3. Longitudinal conductance $G_{xx}$ and transverse conductance $G_{xy}$ of the nanoplate vs. vertically applied magnetic field at different temperatures

Figure S4. Calculated autocorrelation function of conductance fluctuations
Figure S1. Measured longitudinal resistance ($R_{xx}$) of the same device as in the main article as a function of vertically applied magnetic field at temperatures of 2 to 25 K. For clarity, all the curves except for the one at 2 K are successively vertically offset. Here, the longitudinal resistance is obtained from $R_{xx} = V_x/I_x$ using lock-in technique [cf. the measurement circuit setup shown in the inset of Fig. 2(b) in the main article]. As we sweep the field, similar conductance fluctuations superposed on top of the background magnetoresistance are observable at different temperatures. The zoom-in plots in the vicinity of zero field show WAL characteristics at low temperatures and a WAL-WL crossover as temperature increases (cf. the results shown in the main article).

Figure S2. Transverse resistance ($R_{yx}$) of the device vs. vertically applied magnetic field $B$ at different temperatures. As the schematic shown in the inset of Fig. 2(b) in the main article, we measure $V_x$ and $V_y$ simultaneously using lock-in technique and the Hall resistance is obtained by $R_{yx} = V_y/I_x$. (a) $R_{yx}$ at low-field region and (b) $R_{yx}$ over a large region of fields. The sheet carrier density $n_{\text{sheet}}$ is determined from the low-field Hall coefficient as $R_H = 1/ne$ with the Hall coefficient determined by the slope of $R_H = R_{yx}/B$. 
Figure S3. (a) Longitudinal conductance $G_{xx}$ of the device vs. vertically applied magnetic field $B$ at different temperatures. (b) Transverse conductance $G_{xy}$ of the device vs. vertically applied magnetic field $B$ at different temperatures. Here $G_{xx}$ and $G_{xy}$ can be calculated from measured $R_{xx}$ and $R_{yx}$ as $G_{xx} = \frac{R_{xx}}{R_{xx}^2 + R_{yx}^2}$ and $G_{xy} = \frac{R_{yx}}{R_{xx}^2 + R_{yx}^2}$. Longitudinal conductance fluctuations $\delta G$ shown in Fig. 4(a) in the main article are obtained by subtracting the polynomial backgrounds from the measured data shown in (a). The inset in (a) shows zoom-in plots of the conductance around zero field. For clarity, all the curves in (a) except for the one at 2 K are successively vertically offset.

Figure S4. Autocorrelation function $F(\Delta B)$ of the measured conductance fluctuations shown in Fig. 4(a) in the main article. The characteristic field $B_c$ obtained at the half maximum $F(B_c) = \frac{1}{2} F(0)$ in each plot is related to phase coherence length $L_\phi$ by $\Phi_0 = L_\phi^2 B_c$, where $\Phi_0$ is the flux quantum. The inset shows a zoom-in plot of $F(\Delta B)$ at 2K, demonstrating how $B_c$ is determined from $F(\Delta B)$. The extracted values of $L_\phi$ from the autocorrelation functions at different temperatures are shown in Fig. 4(c) in the main article.