The quantum oscillations in different probe configurations in the BiSbTe₃ topological insulator macroflake

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We demonstrate quantum oscillations in BiSbTe₃ topological insulator macroflakes in different probe configurations. The oscillation period in the local configuration is twice compared to the non-local configuration. The Aharonov–Bohm-like (AB-like) oscillation dominates the transport property in the local configuration and the Altshuler–Aronov–Spivak-like (AAS-like) oscillation dominates the transport property in the non-local configuration. The AB-like oscillation period is 0.21 T and the related loop diameter is 156 nm which is consistent with the reported phase coherence length in topological insulators. The Shubnikov–de Haas oscillation frequency is the same but oscillation peaks reveal a π phase shift in the local and non-local configuration. The Berry phase is π in the local configuration and 0 in non-local configuration.

Quantum interference such as universal conductance fluctuations¹, Aharonov–Bohm (AB) oscillation²,³ and Altshuler–Aronov–Spivak (AAS) oscillation, is a wave characteristic of carrier transport. These oscillations originate from a magnetic field flux, Φₒ, through a close loop by two carrier transport trajectories with the same phase in clockwise and counterclockwise directions. The oscillation periodicity of AB and AAS oscillations are related to the of flux quanta, h/2 and h/2e, where the h and e are the Planck’s constant and electron charge, respectively. These oscillations are extremely sensitive to the carrier coherence length and are excellent tools to probe carrier transport properties. With this, it is broadly used to investigate intrinsic characteristics in various kinds of nanowires and patterned nano-structures⁴–¹². The recent study demonstrates the AB-like oscillation in a topological insulator macroflake¹³. The intrinsic mechanism between AB and AAS oscillations are different and the magnetic flux quantum are h/2 and h/2e for AB and AAS interference, respectively which result to half oscillation frequency difference between AB and AAS interference. These two interferences coexist in carrier transports. It is curious that whether one could individually demonstrate the AAS-like oscillation in a mesoscopic system. It is known that as well as the material intrinsic properties, different carrier transport processes leads to different behaviors. One might construct a particular probe configuration to comprehensively detect and optimize the specific carrier transport characteristics.

In this work, we individually realize the experimental demonstration of AB-like and AAS-like oscillations in different probe configurations in the BiSbTe₃ topological insulator macroflake. The carrier transport properties were extracted from the AB-like and AAS-like oscillations and consistent with theoretical predictions. Furthermore, our experimental result revealed that the Shubnikov–de Haas oscillation frequency was the same but oscillation peaks revealed a π phase shift in the local and non-local configurations. The Berry phase is π in the local configuration and 0 in non-local configuration.

Experimental method
Single crystals of BiSbTe₃ were grown using a homemade resistance-heated floating zone furnace (RHFZ). The single crystal grow condition is the same as the previous reports. Our previous work demonstrated that topological insulator (TI) with extremely high uniformity can be obtained using the RHFZ method¹³–¹⁹. Energy-dispersive
X-ray spectroscopy (EDS) confirmed the stoichiometric ratio of the crystal to be Bi:Sb:Te = 1:1:3, while the XRD spectrum confirmed the crystal structure consistent with BiSbTe3 database.

The cleaved BiSbTe3 single crystal flakes were obtained using the scotch-tape method. The cleaved flake geometry is roughly 3 mm in length, 2 mm in wide, and 170 µm in thickness. Gold wires were electrically attached to the cleaved crystal surface using silver paste. The Raman and EDS spectrum support that the crystal is BiSbTe3. Magnetotransport measurements were performed using the standard 4-probe technique in a commercial apparatus (Quantum Design PPMS) with a magnetic field up to 14 T. The B was applied perpendicular to the large cleaved surface. The data points are taken per 100 Gauss at magnetic field region between 6 to 14 T in the steady magnetic field mode, instead of the sweeping magnetic field mode. The data points are taken after the magnetic field is steady at the setting magnetic field for 1 minute.

In this work, we probe the transport characteristics of the BiSbTe3 in two different probe configurations, the local and the non-local probe configurations. Both probe configurations are four-probe method. As shown in the bottom-right inset of the Fig. 1, the applied current, $I_{14}$, flows through the electrode 1 and 4, and the voltage difference, $V_{23}$, is detected at the electrode 2 and 3 in the local configuration. The applied current, $I_{21}$, flows from the electrode 2 to electrode 1, and the voltage difference, $V_{34}$, is detected at the electrode 3 and 4 in the non-local configuration. The resistance, $R$, is determined by the ratio of the detected voltage difference to the applied current in both two configurations. The measured resistances in two configurations follow the same temperature dependence from 300 to 2 K. The residual resistance ratio, $R(2K)/R(300 K)$, reaches 0.07.

**Results and discussion**

The top-left inset of Fig. 1 shows the XRD spectrum and it reveals extremely sharp peaks. That supports the BiSbTe3 is highly crystallized. The bottom-right inset shows the probe configuration in this work. The applied current, $I_{14}$, flows through the electrode 1 and 4, and the voltage difference, $V_{23}$, is detected at the electrode 2 and 3 in the local configuration. The applied current, $I_{21}$, flows from the electrode 2 to electrode 1, and the voltage difference, $V_{34}$, is detected at the electrode 3 and 4 in the non-local configuration. The resistance, $R$, is determined by the ratio of the detected voltage difference to the applied current in both two configurations. To avoid the signal interference due to frequently electrode switching in two different probe configurations. The non-local configuration is performed after one takes all data in different magnetic fields and temperatures in the configuration. The non-local probe configuration is widely used to detect the carrier characteristics in the diffusion process in various kinds of materials and systems.

**Figure 1.** The top-left inset shows the XRD spectrum revealing sharp peaks testifying high quality BiSbTe3 crystal. The bottom-right inset shows the probe configuration in this work. The applied current, $I_{14}$, flows through the electrode 1 and 4, and the voltage difference, $V_{23}$, is detected at the electrode 2 and 3 in the local configuration. The applied current, $I_{21}$, flows from the electrode 2 to electrode 1, and the voltage difference, $V_{34}$, is detected at the electrode 3 and 4 in the non-local configuration. The resistance, $R$, is determined by the ratio of the detected voltage difference to the applied current in both two configurations. The measured resistances in two configurations follow the same temperature dependence from 300 to 2 K. The residual resistance ratio, $R(2K)/R(300 K)$, reaches 0.07.
The oscillation period in local configuration is double of that in the non-local configuration. The $dR/dB$ oscillation amplitude in the local configuration is larger than that in the non-local configuration. To confirm and identify the intrinsic mechanism of the observed different oscillation periods in two configurations, the fast Fourier transform was performed. As shown in the inset of Fig. 3, there are two oscillation peaks in the local configuration and only one peak in the non-local configuration. The second oscillation frequency is double of the first oscillation frequency in the local configuration. The oscillation period is about 0.21 T in the local configuration and the related loop area is $1.92 \times 10^{-14} m^2$. The corresponding diameter is 156 nm which is consistent with the reported phase coherence length for topological insulators. That supports that the observed first oscillation peak of $5T^{-1}$ in the local configuration might originate from the AB interference. Different from the conventional AB oscillation in patterned nano structures or nanowires, the observed AB-like oscillation is speculated to be originated from a series connected elastic scattering trajectory loop in a macroflake. These oscillations are corresponding to the AB-like ($h/e$) and AAS-like ($h/2e$) interference. The oscillation peak in the non-local configuration is the same as the peak position of second oscillation peak in the local configuration. The AB-like oscillation is diminished and only AAS-like oscillation is observed in the non-local configuration. The weak AAS signal was often covered by AB signal and one rarely detects the sole AAS signal in the conventional probe configuration. Our result revealed that one can individually detect the AB-like and AAS-like interference using different probe configurations. The theoretical calculation supports that one could rule out the smearing effect from the interference from loops with different sizes due to the different contribution loop numbers with different size20. The observed single peak originates from the largest loop size which is related to the carrier coherence length.

It is theoretically argued that the AAS-like interference would be suppressed in the case of spin-helical carriers with opposite spins in topological insulators8,10. Our experimental observation revealed clear AAS-like oscillations from surface state carriers. This supports that carriers with spin-helical texture would not eliminate the AAS-like interference. One question arises as to why the AB-like interference gets suppressed while the AAS-like survives in the non-local configuration? Figure 4 shows cartoons of AB-like and AAS-like interferences in a macroflake system with different configurations. Carriers travel half loops and form quantum interference at the other side of the loop in the AB oscillation. Carriers travel a whole loop and form quantum interference at the original position in the AAS oscillation. The sample in this work is in the order of mm which is much longer than the carrier phase coherence length. As shown in Fig. 4, carrier trajectory forms a series of connected AB-like interference loops. The effective quantum oscillation signal is directly related to the combination of these loops. Without the external voltage, carriers would form random-connected AB-like loops in the non-local configuration. The effective loop number would greatly increase in the diffusion process. Following the

both configurations. The oscillation period in local configuration is double of that in the non-local configuration. The $dR/dB$ oscillation amplitude in the local configuration is larger than that in the non-local configuration. To confirm and identify the intrinsic mechanism of the observed different oscillation periods in two configurations, the fast Fourier transform was performed. As shown in the inset of Fig. 3, there are two oscillation peaks in the local configuration and only one peak in the non-local configuration. The second oscillation frequency is double of the first oscillation frequency in the local configuration. The oscillation period is about 0.21 T in the local configuration and the related loop area is $1.92 \times 10^{-14} m^2$. The corresponding diameter is 156 nm which is consistent with the reported phase coherence length for topological insulators. That supports that the observed first oscillation peak of $5T^{-1}$ in the local configuration might originate from the AB interference. Different from the conventional AB oscillation in patterned nano structures or nanowires, the observed AB-like oscillation is speculated to be originated from a series connected elastic scattering trajectory loop in a macroflake. These oscillations are corresponding to the AB-like ($h/e$) and AAS-like ($h/2e$) interference. The oscillation peak in the non-local configuration is the same as the peak position of second oscillation peak in the local configuration. The AB-like oscillation is diminished and only AAS-like oscillation is observed in the non-local configuration. The weak AAS signal was often covered by AB signal and one rarely detects the sole AAS signal in the conventional probe configuration. Our result revealed that one can individually detect the AB-like and AAS-like interference using different probe configurations. The theoretical calculation supports that one could rule out the smearing effect from the interference from loops with different sizes due to the different contribution loop numbers with different size20. The observed single peak originates from the largest loop size which is related to the carrier coherence length.

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Landauer–Büttiker formula in which the detected AB-like signal would be greatly suppressed. On the other hand, AAS-like interference originates from a pair of time-reversal loops. The carrier phase shift by the scattering during the two reverse loops is the same, therefore, the AAS-like would survive the environment scattering. The AAS-like is predicted to be dominant in systems with strong disorders and solely depends on the phase coherence length. These AAS-like loops could individual exist in a mesoscopic system, thus the AAS-like signal is tolerant to the loop number effect.

The previous experiment revealed that the AB oscillation frequency were consistent in the local and non-local configurations in an asymmetric quantum ring. The ring geometry is close to the carrier elastic scattering length. Similar observation is reported in patterned nano-circuits. As we mentioned in the discussion, the signal reduction originates from the massive random-connected quantum loops. These reported focus on their works on the patterned geometry which confines the carrier transport trajectory and that might weaken the loop number effect in the diffusion process. It is worthy to emphasize that no obvious AAS interference signal is observed in both configurations in the asymmetry rings. That might originate from the asymmetry patterned structure and/or weak AAS oscillation signal in the system.

The bottom-right inset of Fig. 5 shows the extracted magnetoresistances as a function of $1/B$ in local and non-local configurations. It reveals periodic oscillations in two configurations and is known as Shubnikov–de Haas (SdH) oscillations. It is interesting that oscillation peaks revealed a $\pi$ phase shift in the local and non-local configurations. The SdH oscillation arises from the successive emptying of Landau levels with the increase of $B$, expressed as $\frac{1}{B} = \frac{2\pi\hbar}{eA_F(N + \beta)}$, where $A_F$ is the cross section area of the Fermi surface, $k_F$ is the Fermi wave vector, $N$ is the Landau level and $\beta$ is the Berry phase. The top-left inset shows the fast Fourier transform of SdH oscillations and a sharp peak at $52\ T^{-1}$ in both configurations. Following the Onsager relation $F = \frac{\hbar k_F^2}{2e}$, where $F$ is the SdH oscillation frequency, the corresponding Fermi wavevector, $k_F$, is $3.9 \ nm^{-1}$ that is consistent with reported $k_F$ of surface state in Bi$_2$Se$_3$ topological insulators. That supports that these SdH oscillations originate from surface state carriers in our Bi$_2$Se$_3$ topological insulator. The $\beta$ could be interfered from the Landau level fan diagram. Figure 5 shows the Landau level fan diagram with magnetoresistance peaks and dips assigned to Landau level $N$ and $N + 0.5$, respectively. The intercept is 0.5 that indicates the $\beta$ is $\pi$ in the local configuration and the intercept is 0 that indicates $\beta$ is 0 in the non-local configurations. The topological insulator surface state carrier is a Dirac Fermion with a Berry phase of $\pi$. Our observation revealed that the different probe configuration would diminish the transport characteristics of Berry phase. Similar behavior is observed in the Dirac semimetal Cd$_3$As$_2$ nanoplates, topological insulator nanoribbon, and AlGaAs/GaAs heterostructure. That might originate from the transport characteristic of diffusion process in the non-local configuration. It needs further investigation to clarify the detail mechanic of the $\pi$ phase shift in different probe configurations.

**Conclusion**

We demonstrate quantum oscillations in Bi$_2$Se$_3$ topological insulator macroflakes in different probe configurations. The oscillation period in the local configuration is double of that in the non-local configuration. The Aharonov–Bohm-like (AB-like) oscillation dominates the transport property in the local configuration and the Altshuler–Aronov–Spivak-like (AAS-like) oscillation dominates the transport property in the non-local configuration. The AB-like oscillation period is $0.21\ T$ and the related loop diameter is $156\ nm$ which is consistent with the reported phase coherence length in topological insulators. The Shubnikov–de Haas oscillation frequency is
Figure 5. The bottom-right inset shows the extracted SdH oscillations in both configurations. The oscillation shifts a π phase in the two configurations. The top-left inset shows the FFT of SdH oscillation in two configurations. The oscillation peak positions are the same. The Landau level fan diagram of two SdH oscillation. The Berry phase is π in the local configuration and 0 in the non-local configuration.

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Received: 8 December 2021; Accepted: 10 March 2022
Published online: 25 March 2022

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**Acknowledgements**
The work was supported by the Taiwan National Science Council through Grants No. MOST 106-2112-M-110-002, MOST 107-2112-M-110-011-MY2, MOST 109-2112-M-110-018, MOST 110-2112-M-110-021, and Center of Crystal Research at National Sun Yat-Sen University. SMH thanks the support of short-term oversea research for scientist and technician from the Taiwan National Science Council. Service plan of core-facility center at NSYSU through MOST110-2731-M-110-001-, MOST108-2731-M-110-001-, MOST107-2731-M-110-001- and MOST106-2731-M-110-001-.

**Author contributions**
S.M.H. conceived and designed the study, analyzed the data and wrote the manuscript. C.L., S.Y. performed the magneto-transport experiment. Y.J.Y., S.H.Y. and M.C. grew the single crystal.

**Competing interests**
The authors declare no competing interests.

**Additional information**

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