Dirac Fermion Kinetics in 3D Curved Graphene

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3D integration of graphene has attracted attention for realizing carbon-based electronic devices. While the 3D integration can amplify various excellent properties of graphene, the influence of 3D curved surfaces on the fundamental physical properties of graphene has not been clarified. The electronic properties of 3D nanoporous graphene with a curvature radius down to 25–50 nm are systematically investigated and the ambipolar electronic states of Dirac fermions are essentially preserved in the 3D graphene nanoarchitectures, while the 3D curvature can effectively suppress the slope of the linear density of states of Dirac fermion near the Fermi level are demonstrated. Importantly, the 3D curvature can be utilized to tune the back-scattering-suppressed electrical transport of Dirac fermions and enhance both electron localization and electron–electron interaction. As a result, nanoscale curvature provides a new degree of freedom to manipulate 3D graphene electrical properties, which may pave a new way to design new 3D graphene devices with preserved 2D electronic properties and novel functionalities.

Graphene is a 2D atomic-layer material with excellent electrical, chemical, thermal, and mechanical properties for a wide range of applications.1–12 However, practical applications of graphene are often limited by the intrinsic 2D morphology which only provides very limited areal mass loading and thus insufficient areal device performances. To amplify the device performances of 2D graphene, one approach is to construct 3D graphene nanoarchitectures (denoted as 3D graphene). Various 3D graphene materials have been developed in the past decade.13–21 However, it remains challenging to preserve the 2D graphene characters, such as Dirac fermions and 2D electron transport properties, in 3D graphene because of the introduction of crystal defects, loss of crystallinity, restacking of graphene sheets, and high contact potentials between discrete graphene components. Recently, we have successfully fabricated 3D graphene by nanoporous metal based chemical vapor deposition. The resulting 3D graphene is constructed by a single graphene sheet with a bicontinuous and open porous structures (denoted as graphene sponge) and can fully preserve the 2D electronic properties of graphene with a large accessible specific surface area and high areal mass loading for a wide range of functional and structural applications.22–26

One of the intriguing subjects of 3D graphene is the transport properties, which are an indispensable factor for electronic device applications. Typical structural components of the graphene sponge are 3D curved surfaces with possible

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grain boundaries, topological defects, and quasiperiodic structures. Theoretically, 3D curved surfaces give additional phases to conduction electrons through pseudomagnetic fields, and, especially, a closed-loop path around topological defects which can flip the valley and pseudospin of an electron. As a result, an intravalley and an intervalley electron scattering could be enhanced when an electron propagates on 3D curved surfaces. The formation of an energy gap, inversely proportional to the period of the 3D curved structure, has also been predicted from 3D periodic graphene. Experimentally, the graphene sponge with a pore size (i.e., equivalent to curvature radius) of hundreds of nanometers shows graphene-like electric and optical properties. Nearly 1000 times larger capacitance and extremely low transmission in the optical response have been observed as a consequence of the increase in the areal mass loading through 3D integration. However, since the curvature radii of these graphene sponge are orders of magnitude larger than the interatomic distance of graphene, the geometric effect of curvature on electronic properties is anticipated to be insignificant, and the nonlinear magnetoresistance and Hall effects as well as broadband Dirac plasmonic absorptions could be the consequence of topological and geometric effects. It is highly desired to fabricate high-crystallinity 3D monolayer graphene with a small curvature radius in the range from several to tens of nanometers by which the curvature effects on electronic behavior of graphene can be explored experimentally.

In this report, we systematically investigated the electronic states and electrical properties of graphene sponge with the curvature radius ranging from 25 to 1000 nm based on our recent success in fabricating high-quality 3D graphene using a nanoporous-metal-based chemical vapor deposition (CVD). This study provides experimental insights into the properties of 2D electrons on 3D curved surfaces of graphene and has important implications in designing and creating 3D graphene-based electronic devices.

The graphene sponges grown under different CVD conditions show 25–50, 50–150, and 500–1000 nm curvature radius, imaged by scanning electron microscopy (SEM) (Figure a–c; and Figures S1 and S2, Supporting Information). Although the substrates and CVD conditions are different, these samples have nearly identical bicontinuous nanoporous morphology in both geometry and topology except the difference in feature length. The average pore size and specific surface areas of the graphene sponges were quantitatively measured by the nitrogen adsorption/desorption method with Barrett–Joyner–Halenda and Brunauer–Emmett–Teller models. The BJH pore sizes are well consistent with the SEM images (Figure S3, Supporting Information), and the BET surface areas range from 758.9 to 1260 m² g⁻¹. The low-magnification transmission electron microscopy (TEM) image (Figure 1d) of the sample with a 25–50 nm curvature radius (abbreviated as 25–50 nm sample) presents a bicontinuous porous structure that is comprised of a smoothly interconnected graphene sheet. The corresponding selected area electron diffraction pattern, as the inset of Figure 1d, shows sharp diffraction spots, verifying the high crystallinity of the graphene. The high-resolution TEM image (HRTEM) of the graphene (Figure 1e) taken from a curved region reveals the existence of topological defects, such as 5 and/or 7 membered rings (yellow circles), with local lattice distortions to accommodate the highly curved graphene lattices (red line).

Raman spectra reveal the relationship between the curvature radius and defect density. The 25–50 nm sample gives rise to a higher intensity of D bands (Figure 1f; and Table S1, Supporting Information) than the graphene sponges with larger pore sizes, suggesting that a higher curvature leads to more geometrically-required defects. According to the intensity ratio of 2D and G bands ($I_{2D}/I_{G}$: 4.6–4.7), the graphene sponges are mainly comprised of high-quality monolayer graphene. The average distance between topological defects on the graphene lattice was estimated by the ratio of D and G bands in the Raman intensity.
spectra \((I_D/I_G)\) with Tuinstra–Koenig relation\(^{42-44}\) of \(I_D/I_G = C(\lambda)/L_D\), where \(C(\lambda)\) is a proportionality constant at the excitation laser wavelength \(\lambda\) and \(L_D\) is the average distance between the defects. The \(L_D\) values of 25–50 nm sample \((I_D/I_G = 0.52)\) is \(\approx\)10–20 nm, whereas the \(L_D\) values of 50–150 nm \((I_D/I_G = 0.20)\) and 500–1000 nm \((I_D/I_G = 0.04)\) samples are about 20–50 and over 100 nm, respectively. It is worth noting that the difference in the defect density between the samples with the smallest and largest pores is only several times while the pore size (curvature radius) difference is 1–2 orders of magnitude. Therefore, out-of-plane elastic strains of graphene lattices may carry most of the curvature, while the topological defects may only play a minor role in forming 3D curved graphene. As a result, the obvious enhancement of \(D’\) band in the 25–50 nm sample is mainly contributed by intraband resonant Raman scattering from the 3D curved surface compared to larger pore size samples (Table S1, Supporting Information) and 2D graphene on a Cu sheet.\(^{5,45}\)

Moreover, the binding state and quantitative chemical composition of the graphene sponges were investigated by X-ray photoelectron spectroscopy (XPS) (Figure S4, Supporting Information).

To elucidate the curvature dependence of electronic states of the graphene sponges, we performed photoemission spectroscopy (PES) measurements of the 3D graphenes with 25–50 nm, 50–150 nm (abbreviated as 50–150 nm sample), and 500–1000 nm (abbreviated as 500–1000 nm sample) in curvature radius (Section 2.3, Supporting Information) using a customer-designed PES system (MBS A-1 spectrometer, MB Scientific AB) with a high-flux helium discharge lamp and a toroidal grating monochromator (MB Scientific AB).\(^{46}\) Graphene sponge samples were set at parallel to a photoelectron analyzer and the incident angle of photons with respect to sample normal is 45°. The energy and angular resolutions are 32 meV and ± 0.1°, respectively. As different orientations of graphene planes in the graphene sponges are exposed to the incident photons due to the unique structural nature of the graphene samples,\(^{23}\) the photoelectrons are emitted at various angles with respect to the graphene planes and thus the emission angle (momentum) dependence of photoelectrons is smeared out. As a result, only angle-integrated PES spectra can be obtained for investigating the electronic structure, especially valence bands, of the 3D curved graphene (Figure 2a).

Valence band structures in the 1000 nm pore sample have several features and resemble that of highly oriented pyrolytic graphite (HOPG),\(^{47}\) the peaks around 4–9 eV of the 25–50 nm sample have much richer structures which are probably from \(\pi + \sigma\) orbitals of highly curved graphene lattices. Compared to the 50–150 nm sample, the peak around 3 eV corresponding to \(\pi\) orbitals becomes much weaker in the 25–50 nm sample, which also indicates the increase in the local interlayer interactions, the \(sp^3\) configurations, and topological defects from the highly curved graphene lattices by reducing the curvature radii. Surprisingly, the density of states (DOS) near \(E_F\) in all samples keep the linear-like character of the 2D Dirac fermions (inset of Figure 2a). However, the slopes of the linear DOS gradually decrease with curvature radii. Therefore, the Dirac fermions system can be well preserved in the 3D curved graphene regardless of the curvatures, and importantly, it can be tuned by the highly curved surfaces.

The electrical transport properties of the graphene sponges were measured using electric double layer transistor (EDLT) devices to investigate the curvature-dependent electronic states. Figure 2b shows a gate voltage dependence of electrical resistance for the graphene sponges with various curvature radii (Figure S5, Supporting Information). The electrical resistances

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**Figure 2.** Angle-integrated photoemission spectra (PES) of graphene sponges measured by He IIa resonance line \((h\nu = 40.814 eV)\) at room temperature. a) 25–50 nm (orange), 50–150 nm (blue), and 500–1000 nm (red) curvature radii samples. The inset shows the angle-integrated PES near the Fermi level. The black dash lines are the linear extrapolations to the Fermi level. b) Longitudinal resistance against the gate voltage \(V_G\) for the graphene sponge EDLT with 25–1000 nm curvature radii at room temperature.
show ultralow values (0.8–2.2 Ω for the 500–1000 nm sample, 1.5–6 Ω for the 50–150 nm sample, 16–33 Ω for the 25–50 nm sample), which are ten to thousand times lower than that of 2D CVD graphene (500–15 000 Ω)[5,48] (Table 1). All samples show an electrical resistance peaks in the $V_g$ range from $-0.5$ to 0.5 V, demonstrating the ambipolar electronic states of the graphene sponges.[34] The resistance on/off switching ratio is comparable between the graphene sponge samples (on/off ratio: 1.3–5) and much lower than those of 2D graphene EDLT (on/off ratio: $\approx 10$)[49,50] indicating no obvious bandgap formation across the entire graphene sponge samples. The systematic increase in the electrical resistance with the curvature radii decrease indicates that the curvature radius could be an essential parameter to tune the electronic properties of graphene sponges.

The dependence of the electrical resistance on the curvature radius was systematically investigated at low temperatures under magnetic fields. Figure 3a shows the temperature ($T$) dependence of the electrical resistance at zero magnetic fields for the samples with various curvature radii. The electrical resistance values progressively increase as the curvature radius decreases. The resistance curves of all the samples show a negative slope in the temperature ranges from 2 to 300 K. Figure 3b,c are the zoom-in plots from the low-temperature region to elucidate the temperature dependence of the electrical conductance ($G$). The temperature–conductance curves obey a logarithmic law at low-$T$, which is prominent for the 25–50 nm sample. Magnetic field ($B$) dependence of magnetoresistance was investigated, as shown in Figure 3d–f. For the 500–1000 nm sample, positive magnetoresistance is almost linear against $B$ at 300 K. When the temperature decreases, the positive linear magnetoresistance is gradually suppressed. Below 10 K, negative magnetoresistance cusp develops at a low-$B$ region, as shown in the inset of Figure 3d. For the 50–150 nm sample, the positive linear magnetoresistance amplitudes are reduced and the low-$B$ cusps are enlarged at low temperatures. Interestingly, the 25–50 nm sample exhibits a distinctive magnetic field dependence. The positive linear magnetoresistance curves in the 3D graphene with a large curvature radius are completely replaced by the negative ones for all tested temperatures. At 1.9 K, a broadened negative magnetoresistance cusp is developed at low-$B$, and it smoothly connects to the shallow convex curve at high-$B$.

According to the tight-binding model of curved graphene, the overlap of $\pi$ electrons outside the curved surface decreases but inside the curved surface increases (Section 3, Supporting Information). As a result, the electron density tends to increase outside the curved surface due to Coulomb repulsion, and the transfer integral $t$ (i.e., hopping between A and B sublattices of graphene) decreases with curvature radii. In this case, the effective mass $m^*_{\pi}$ is expected to increase with the decrease of the curvature radii. Experimentally, the linear electron DOS in the PES spectra of the graphene sponges demonstrate that the electronic state of 2D graphene is well preserved in the 3D curved nanostructure, which is consistent with the electrical transport measurements. While the electrical resistance, being proportional to the effective mass $m^*_{\pi}$, increases with the decrease of curvature radii, the gradient of PES spectra near the $E_F$, which is also associated with effective mass $m^*_{\pi}$, systematically decreases with curvature radii. Therefore, the inconsistence indicates that the geometric effect of 3D curvature may not be simply expected by the tight-binding model in the curved graphene. Alternatively, the local quasiperiodic potential, the circular pipe structure, and the high curvature induced pseudomagnetic fields may lead to the Bragg reflections of electron waves (i.e., energy gap opens locally).[30] In this case, PES spectra could become a sum of massless and massive Dirac fermions and the changes of the DOS near $E_F$ depend on their volume fractions. Consequently, while the graphene sponges well preserves the electronic properties of 2D graphene, the 3D curved surface provides an additional degree of freedom to manipulate the 2D electron behavior and hence electronic properties.

In 2D disordered electron systems, diffusive electron motions from dominant elastic scattering may cause the interference among electron propagation pathways and results in the weak localization (WL).[31,52] The WL adds a logarithmic-law in the temperature–conductivity curves but it is difficult to be distinguished from electron–electron interactions (EEl)[53] In order to identify the WL effects, the magnetocconductivity measurement is essential. In 2D graphene, the intervalley backward scattering from charged impurities, edges, grain boundaries, etc., is the primary source of the WL corrections.[32,54,55] In the graphene sponges, 3D curved surfaces, together with grain boundaries and topological defects, could be the sources of intravalley electron scattering and/or intervalley electron

### Table 1. Electric performances of graphene sponges. Electrical conductances are normalized by the geometrical dimension of graphene sponge.

| Sample | Electrical conductance at 300 K [S] | Capacitance [mF cm$^{-2}$] | Carrier mobility [$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$] | Error bar |
|--------|-------------------------------|------------------|------------------|-----------|
| 25–50 nm graphene sponge | 0.03–0.05 | 2.0–3.6 | 7–8 | 4 |
| 50–150 nm graphene sponge | 0.06–0.5 | 1.0–2.5 | 100–200 | 100 |
| 500–1000 nm graphene sponge | 0.5–1 | 0.40–1.0 | 600–700 | 400 |
| CVD graphene | 10$^{-4}$–10$^{-3}$ | 0–0.003 | 550–25 000 | N/A |

$^a$Sample dimensions for normalized electrical conductance are 1 mm channel length, 1 mm width, and 0.030 mm thickness; $^b$Results in the exfoliated graphene; $^c$Carrier mobility of the graphene sponges was estimated from Hall mobility in the single carrier model and Equation (SE13) in the Supporting Information. Hall mobility is calculated using the electrical conductance and Hall coefficient defined at maximum magnetic fields. The second derivative of Equation (SE13) in the Supporting Information for 2D-CVD graphene cannot be estimated since Hall resistivity is linear against magnetic fields (Section 4.2, Supporting Information).
The WL could be restored by the inter-valley scattering through the mixing of \( K \) and \( K' \) valleys in the graphene electronic states. In fact, the number of possible scattering sources on the electron pathways increases when the curvature radius decreases. The negative magnetoresistance cusp in the low-\( B \) region, as a consequence of dephasing of WL states, gradually develops with the decrease of curvature radii and changes to the broadened negative one at the curvature radius of 25–50 nm. Note that the magnetoresistance at high-\( B \), i.e., positive curves for the 50–1000 nm samples and shallow convex negative curve for the 25–50 nm sample, will be discussed in the next section.

To analyze the WL in the magnetoconductance where the low-\( B \) cusp is developed, we employed two models to fit the experimental data. The model I, formulated in Equation (1), only considers the back-scattering effect\(^{58}\) and the model II (Equation (2)) includes the graphene electronic structures\(^{54,55}\)

\[
\Delta \sigma / \sigma_0 = \frac{e^2}{\pi \hbar \sigma_0} \left[ F\left( \frac{B}{B_0} \right) - F\left( \frac{B}{B_0 + B_i} \right) - F\left( \frac{B}{B_0 + B_i + B_{i'}} \right) \right] 
\]

(1)

In the equations above, \( F(z) = \ln(z) + \psi(0.5 + z^{-1}) \), \( \psi(x) \) is a digamma function. \( B_0, B_i \), and \( B_{i'} \) are proportional to the phase breaking rate \( \tau_x^{-1} \), the intervalley scattering rate \( \tau_i^{-1} \), and the intravalley scattering rate \( \tau_\ast^{-1} \), respectively. The low-\( B \) cusps in the magnetoconductance curves are fitted using Equations (1) and (2), as shown in Figure 4a–c. The fitting ranges are limited to low-\( B \), where the low-\( B \) cusps in the magnetoconductance are developed. The magnetoresistance in high-\( B \), which has different origins, will be discussed in the next section. Fitting parameters for Equations (1) and (2) at the lowest temperatures are displayed in Figure S6 in the Supporting Information. The obvious increase in the scattering rates with decreasing of the curvature radius is confirmed by both models (Figure 4a–c; and Figure S6, Supporting Information). The fact that the excellent fittings of the low-\( B \) data from the three samples can be achieved from both models also indicates that intervalley scattering is essential, leading to the weak localization in the
magnetoconductance. It is worth noting that large errors in fitting results of Equation (2) are due to the limited fitting range since the effect of weak antilocalization (WAL) (i.e., negative magnetoconductance curve) is involved in Equation (2). For the fitting parameters of Equation (2), the $B_i$ and the $B^*$ increases nearly 10–100 times when the curvature radius decreases to 25–50 nm. It suggests significant enhancements of intervalley and intravalley electron scattering from the geometric effect of the 3D curvature, which is consistent with the development of D and D' band in the Raman scattering. For quantitative comparison, $L_i = \left(\hbar/4eB_i\right)^{1/2}$ is in the range of 91–100 for 500–1000 nm sample, 40–47 for 50–150 nm sample, 14–16 for 25–50 nm sample, being approximate to the $L_D$ measured by the Raman spectra. Consequently, the WL correction in the electrical conductance is controlled by 3D curvature of the graphene sponges.

The high-$B$ magnetoresistance is dominated by the positive linear curves for the 500–1000 nm sample and decreases to be weakly positive for the 50–150 nm sample. The positive magnetoresistance in graphene is usually interpreted by WAL as a consequence of the $\pi$ Berry’s phase of the massless Dirac fermion.\(^{54,55}\) However, the WAL corrections should be suppressed with the increase of temperatures, which is opposite to the experimental observations. To examine the WAL effects in the graphene sponges, temperature dependence of reduced electrical conductance ($\Delta G$), i.e., electrical conductance subtracting the electrical conductance at the lowest temperatures, is studied. For 50–150 nm sample, the logarithmic temperature-reduced conductance curves are first suppressed around 0.5 T due to weak localization and then enhanced from 0.5 to 10 T from weak antilocalization. The saturation of the normalized $A$ at around 10–15 T is due to the electron–electron interactions (EEIs). For 25–50 nm, the normalized $A$ is almost constant around 5–15 T, originating from the EEIs.

### Figure 4

- **a–c)** Magnetoconductance curves of graphene sponges with 25–1000 nm curvature radii. Broken and solid black lines are the fitting results of Equations (1) and (2) to extract the weak localization corrections from the magnetoconductance curves. $B_0$, $B_i$, and $B^*$ are the fitting parameters that are proportional to the phase breaking rate $\tau^{-1}$, the intervalley scattering rate $\tau_i^{-1}$, and the intravalley scattering rate $\tau^*^{-1}$.
- **d,e)** Temperature-reduced conductance ($\Delta G$) curves for 50–150 and 25–50 nm under various magnetic fields. $\Delta G$ are calculated by subtracting the conductance at the lowest temperatures from raw conductance curves. The blue lines present the fitting results using $\Delta G = A\log T + B$.
- **f)** Magnetic field dependence of gradients of logarithmical temperature–conductance curves $A$, normalized by $A$ at 0 T ($A_{0T}$). The error bars are estimated from the results of the least-squared fitting.
- **g)** The magnetic field dependence of resistance after subtracting the WL corrections in Equations (1) and (2) for 25–50 nm sample. The red lines present the fitting results using quadratic curves.
A gradient of the log $T$ curve observed at zero magnetic fields is once reduced at 0.5 T and is enhanced from 3 to 10 T. These suppression and enhancement of log $T$ curves at low temperatures demonstrate the dephasing of WL and WAL corrections by magnetic fields. The ratio of WAL to the positive linear magnetoresistance is decreased $\sim 5$–10% from gradients of log $T$ curves. Therefore, the present positive linear magnetoresistance mainly originates from semiclassical transport. In the 3D curved graphene structure, the effective transverse magnetic field locally weakens depending on the angle between the 3D curved surface and the magnetic fields, which can result in the positive linear magnetoresistance from the semiclassical model (Sections 4.1 and 4.2, Supporting Information). In this scenario, the suppression of the positive linear magnetoresistance observed from 50–150 nm sample, in comparison with that from 500–1000 nm can be explained by the decreased carrier mobility from the additional electron scattering caused by the 3D curved surfaces. For the 25–50 nm sample, the positive magnetoresistance originating from the semiclassical transport and the WAL corrections, is completely suppressed by the electron scattering effects from 3D curvature and only the shallow convex negative magnetoresistance is left, together with the WL correction at low $B$. This broad negative magnetoresistance at high $B$ can be attributed to EElIs. When the curvature radius further decreases to 25–50 nm, highly curved 3D surface significantly enhances both intravalley and intervalley electron scattering $(B_i/B_v , B_i/B_v > 1 ; B_v , B_i \times \tau^{-1} , r^{2} , r^{2})$. Such diffuse electron motion could amplify the EElIs between scattered electrons.

The magnetoresistance subtracting the WL correction as shown in Figure 4c using Equations (1) and (2) (Open circle and square in Figure 4g) is proportional to $-B^2$ curves (red lines).

This quadratic curve is the characteristic behavior of the EEIs. To elucidate a component of the EEIs corrections in the temperature–conductance curves, which are well known as log $T$ curves, the temperature dependence of electrical conductance at high $B$ was investigated because the log $T$ correction originating from EEIs is insensitive to the magnetic fields in the present conditions, in contrast to the WL correction. When WL corrections are well suppressed above 5 T, the electrical conductance proportional to log $T$ is represented up to 15 T. The gradients of log $T$ curves are almost constant as shown in Figure 4e,f, consistent with the EEIs corrections. The saturation of the gradients of log $T$ curves above 10 T for 50–150 nm samples as shown in Figure 4d,f can also be interpreted as EEIs corrections. For 25–50 nm samples, the gradients of log $T$ curves are obviously larger than those of 50–150 nm samples, indicating the enhancement of the EEIs corrections by the electron scattering of the 3D curved surface. Therefore, the highly curved 3D surface significantly affects the transport properties of 2D graphene by suppressing the $\pi$ Berry’s phase transport and enhancing the electron–electron interactions (Section 4.5, Supporting Information).

We make a comparison of electronic performances of graphene sponges with 2D graphene, as shown in Table 1, for understanding the curvature effects in graphene properties. Comparing with 2D graphene with electrical conductance of $10^{3} - 10^{4}$ $S^{2}$, [48,63,64] and capacitance of 0–0.005 mF cm$^{-2}$,[49] the 500–1000 nm graphene sponge can be simplified as the parallel circuits of a single graphene sheet since the electrical capacitance of the graphene sponge is $\sim 1000$ times higher than that of 2D graphene[48] (Figure S7, Supporting Information). Under this assumption, it can be understood that the suppression of the electrical conductance in the 25–50 and 50–150 nm samples comes from additional scattering effects originating from the geometry of graphene sponges (Figure S8, Supporting Information). Thus, while the capacitance of the graphene sponges can be enhanced by the increase of the integration efficiency in the graphene nanoarchitectures, the electrical conductance could be limited by the electron scattering effects from 3D curvature.

The Hall mobility for 500–1000 nm sample is calculated from normalized electrical conductance. The Hall coefficient at maximum magnetic fields is 600–700 cm$^{2}$V$^{-1}$s$^{-1}$, which is comparable with the lower bound of 2D-CVD graphene. The value decreases with the curvature radius, as shown in Table 1. However, the conventional Hall mobility may underestimate the carrier mobility because 3D electron pathways can weaken the actual transverse magnetic field from place to place. To estimate the actual carrier mobility, we previously proposed a simple model based on the simplified 3D graphene structures[34,36] (Sections 4.1 and 4.2, Supporting Information), although a more accurate model would require a sophisticated method.[65] Carrier mobility of the 25–50 nm sample is 10–100 times lower than that of the 500–1000 nm sample, which is quantitatively in agreement with the enhancement of $B_v$, $B_i$, and underline the additional effects in electron scattering and carrier mobility from the 3D curved structure.

We have elucidated the effects of 3D curvatures on the electronic states and electrical transport properties of graphene. It has been found that the electronic states of 2D graphene, i.e., linear DOS and ambipolar electronic transport properties, can be well preserved in 3D curved graphene with the curvature radius down to 25–50 nm. The 3D curvature can effectively suppress the electron DOS near the Fermi energy, providing a new degree of freedom to tune the electronic properties of graphene. Moreover, the curvature enhances the scattering of 2D Dirac fermion through the electron scattering (interference) in the 3D curved space. As a result, the conductivity corrections of both the electron localization and electron–electron interaction suppress the electrical transport in 3D curved graphene. This study experimentally unveils the effect of 3D curvature on electronic states and electrical transport properties of graphene, providing new insights into the 2D electron kinetics in 3D nanoarchitecture with intrinsic curvature and essential knowledge to amplify various excellent properties of graphene for 3D device applications.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

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