Berry curvature dipole senses topological transition in a moiré superlattice

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Topological aspects of the electron wave function—including the Berry curvature and Chern number—play a crucial role in determining the physical properties of materials. Although the Berry curvature and its effects in materials have been studied, detecting changes in the Chern number can be challenging, particularly changes in the valley Chern type. In this regard, twisted double bilayer graphene has emerged as a promising platform to gain electrical control over the Berry curvature hotspots and the valley Chern numbers of topological flat bands. In addition, strain-induced breaking of the threefold rotation symmetry leads to a non-zero first moment of Berry curvature (called the Berry curvature dipole). Here we show that a sign change in the Berry curvature dipole detects topological transitions in the bands. In twisted double bilayer graphene, the perpendicular electric field simultaneously tunes the valley Chern number and Berry curvature dipole, providing a tunable system to probe the topological transitions. Furthermore, we find hysteresis in the transport response that is caused by switching of the electric polarization. This holds promise for next-generation Berry-curvature-based memory devices. Our technique can be emulated in three-dimensional topological systems to probe topological transitions governed by parameters such as pressure or anisotropic strain.

Exploring materials with new topological phases and probing their symmetries has been at the forefront of modern research. Topology is often characterized by Berry curvature that manifests as the quantum Hall effect or anomalous Hall effect in magnetic materials. Although these effects have led to many breakthroughs in physics, these linear responses vanish in systems that preserve time-reversal symmetry. However, even in time-reversal-symmetry-protected systems, broken inversion symmetry can lead to the first moment of Berry curvature, namely, a Berry curvature dipole (BCD), when further spatial symmetries are reduced. In the presence of an a.c. current (of frequency \(\omega\)) in such a system, the BCD can drive a second-order electrical response, namely, the nonlinear Hall (NLH) voltage with zero (d.c.) and second-harmonic (2\(\omega\)) frequencies. Aligned with the recent interest in various nonlinear phenomena such as nonlinear optics, there is a rapidly growing interest to look for quantum materials that host the NLH effect.

The topological phase of quantum materials can be characterized by the band-specific topological invariant Chern number. Often, systems undergo a transition between topological phases and these transitions are hard to detect, unlike phase transitions of the order parameter. Recent proposals suggest that topological transitions are accompanied by simultaneous changes in the BCD. Moiré systems are known to be natural candidates to host topological bands. However, time-reversal symmetry dictates the Chern numbers from two valleys, namely, \(K\) and \(K'\), to be opposite, making the total Chern number \(C_\text{K} + C_\text{K'} = 0\). In such a scenario, BCD can be used as an indicator of the underlying topological transition of the valley Chern type, that is, the transition in \(Z = (C_\text{K} − C_\text{K'})/2\). Unlike the quantum Hall effect or anomalous Hall effect, the approach based on the BCD does not require explicitly breaking the time-reversal symmetry. Although the NLH effect has been observed for transition metal dichalcogenides and corrugated bilayer graphene, the experimental study in two-dimensional moiré systems is limited. Furthermore, topological transitions along with BCD have not been experimentally observed thus far.

Recently, the observation of several novel phenomena in moiré systems such as magic-angle twisted bilayer graphene has attracted attention. Flat bands in twisted systems give rise to various electronic correlation phenomena such as Mott insulators and superconductivity. In particular, the observation of anomalous Hall effect, orbital ferromagnetism and Chern insulating states point to the rich topology of these twisted systems. Flat bands of moiré systems are also susceptible to symmetry breaking by strain. Together with the fact that spatial symmetry breaking can lead to non-zero BCD, bands in two-dimensional moiré systems offer an interesting platform to electrically tune the topology and detect it via the NLH effect.

In this work, we use twisted double bilayer graphene (TDBG), in which two copies of bilayer graphene are stacked together with a small twist angle of approximately 1.1°, as a candidate system to study topological transitions using the NLH effect. Although the flat bands in TDBG host correlation-induced physics as in twisted bilayer graphene, TDBG is additionally equipped with electric-field tunability. The perpendicular electric field, apart from modulating the band structure, can also change the valley Chern number of a flat band. Additionally, almost touching flat bands with small tunable energy gaps of a few millielectronvolts in TDBG give rise to a large Berry curvature in this system. We use electric-field tunability to demonstrate that TDBG hosts substantially large BCD due to strain. The BCD abruptly changes sign and this can be attributed to a topological transition, a change in valley Chern type.
number, with the electric field. The BCD sign change across a topological transition is further confirmed by our theoretical calculation. Additionally, hysteresis in both longitudinal resistance and NLH signal as a function of the electric field suggests switching between the metastable states.

In TDBG, broken inversion symmetry allows non-zero Berry curvature (Ω). Additionally, the imaging of small-angle twisted moiré devices reveals strain that breaks threefold rotational (C₃) symmetry. Such reduced symmetry makes the Berry curvature distribution non-symmetric and anisotropic over the moiré Brillouin zone (mBZ), leading to non-zero BCD (Λ) given by

\[
\Lambda = \sum_n \int_{\text{mBZ}} \frac{dk}{(2\pi)^2} \frac{\partial \epsilon_n}{\partial q_y} \frac{\partial f(\epsilon_n)}{\partial \epsilon_n}. \quad (1)
\]

Here \( \alpha \) denotes the spatial index \((x,y)\), \( \epsilon_n \) is the energy of the \( n \)th band and \( f(\epsilon_n) \) is the Fermi–Dirac function. In equation (1), a sum over all the bands crossing the Fermi energy is implied. To calculate the BCD in TDBG, we consider distorted hexagonal mBZ with the C₃ symmetry broken by strain (Fig. 1a). The effect of C₃ symmetry breaking is reflected in the Berry curvature plots (Fig. 1b,c). Figure 1d shows the band structure for TDBG with a twist angle of 1.10° under 0.1% strain with Ω, the flat bands (indicated by different colours). Together, non-zero Berry curvature and broken C₃ symmetry generate a non-zero BCD (Fig. 1e; Methods and Supplementary Sections I–III provide the calculations). In a two-dimensional system in the \( x-y \) plane, a non-zero \( \Lambda \) induces a second-harmonic response via the equation \( j^{\text{2nd}} \propto z \times E^{\text{1st}} (\Lambda \cdot E^{\text{1st}}) \), which can be detected by measuring...
Fig. 2 | Longitudinal and NLH voltages in TDBG. a, Longitudinal voltage ($V_{xx}^\omega$) as a function of filling factor ($\nu$) and perpendicular electric displacement field ($D$) measured by sending an a.c. current of $I=100\,\text{nA}$ with frequency $\omega=177\,\text{Hz}$ at a temperature of $1.5\,\text{K}$. The top x axis indicates the charge density ($n$). The colour bar (bottom left) indicates the corresponding values of the longitudinal resistance ($R_{xx}$). The schematics (right) depict the band structures with energy in the $y$ axis and the density of states in the $x$ axis for different regimes of $D$ (indicated by the arrows). The isolated flat bands are marked in red, whereas the dispersive moiré bands are marked in blue. b, Second-harmonic NLH voltage ($V_{xy}^{\omega^2}$) as a function of $\nu$ and $D$ simultaneously measured with $V_{xx}^\omega$ in a. The $V_{xy}^{\omega^2}$ peaks near the CNP gap and moiré gaps. The ($\nu$, $D$) points marked by the crossed circles are used in d. c, Line slices of $V_{xy}^{\omega^2}$ versus $\nu$ for different values of $D$. d, Linear dependence of $V_{xy}^{\omega^2}$ on simultaneously measured ($V_{xx}^\omega$) by varying current as a parameter up to $80\,\text{nA}$ at $T=1.5\,\text{K}$ for two biasing points of $(\nu, D)$. e, $V_{xy}^{\omega^2}$ versus $I$ for $\nu=−4$ and $D/\epsilon_0=−0.04\,\text{V nm}^{-1}$. The coloured schematics indicate the orientation of the current and voltage terminals. Also, $V_{xy}^{\omega^2}$ reverses the sign when the orientation of both voltage and current probes are simultaneously flipped, indicating the second-order nature of the NLH voltage.

We fabricate multiple TDBG devices to measure NLH voltage, which probes the BCD\cite{11,18}. The dual-gate geometry allows independent control of the charge density ($n$) and perpendicular electric displacement field ($D$) (Methods). Figure 1f shows the schematic of our measurement to probe the NLH effect. We send a current with low frequency $\omega$ and measure the longitudinal voltage ($V_{xx}^\omega$) and second-harmonic NLH voltage ($V_{xy}^{\omega^2}$) at frequencies $\omega$ and $2\omega$, respectively. In Fig. 1g, we show $V_{xx}^\omega$ and $V_{xy}^{\omega^2}$ as a function of the moiré filling factor ($\nu$) at zero displacement field for a TDBG device with a twist angle of 1.10°. Here $\nu=4n/n_0$ with $n_0$ representing the number of carriers to fill one moiré band and the factor 4 is due to spin and valley degeneracy. The peaks in $V_{xx}^\omega$ at $\nu=±4$ correspond to the two moiré gaps. The substructures in the $V_{xx}^\omega$ peaks (Fig. 1g, arrows) result from the slightly different twist angles, indicating an angle inhomogeneity of approximately 0.03°—a signature of strain\cite{50} that causes BCD in our system. In Fig. 1h, we plot $V_{xx}^\omega$ and $V_{xy}^{\omega^2}$ for a non-zero $D$ that creates a gap at $\nu=0$ (charge neutrality point (CNP)). We find that NLH voltage $V_{xy}^{\omega^2}$ is high in the vicinity of the band edge around the moiré gaps at $\nu=±4$ as well as the CNP gap in our strained TDBG devices.

We now study the evolution of $V_{xx}^\omega$ and corresponding resistance ($R_{xx}$) in the experimentally accessible parameter space of $\nu$ and $D$ (Fig. 2a). The schematics in Fig. 2a (right) show changes in the underlying band structure with $D$ (Supplementary Section III shows the calculated band structure). A finite displacement field opens up a gap at the CNP between the conduction and valence flat bands. These flat bands are separated from the remote moiré bands by two moiré gaps, which close at larger values of $D$. Apart from the peaks in $V_{xx}^\omega$ corresponding to the CNP gap at $\nu=0$ and the moiré gaps at $\nu=±4$, we observe other features like the cross towards the hole side ($−4<\nu<0$) and the halo around $D/\epsilon_0=±0.3\,\text{V nm}^{-1}$ towards the electron side ($0<\nu<4$). These characteristic features of the TDBG within the partial fillings of the flat bands are likely to be connected to structures in the density of states\cite{51}.
Figure 2b shows the evolution of the NLH voltage $V_{xy}^{(2)}$ in the same parameter space of $\nu$ and $D$. In Fig. 2c, we have plotted a few line slices of $V_{xy}^{(2)}$ around $\nu = 0$ for different $D$ values. We find that $V_{xy}^{(2)}$ peaks near the gaps at $\nu = 0$ (CNP gap) and $\nu = \pm 4$ (moiré gaps). The coincidence of the NLH voltage with the TDBG bandgaps reveals that the Berry curvature hotspots, and hence the BCD, predominantly reside in the vicinity of the band edges. We further explore this behaviour in Fig. 3.

Further, $V_{xy}^{(2)}$ should scale quadratically with the in-plane a.c. electric field of frequency $\omega$. We verify the quadratic scaling in Fig. 2d from the linear behaviour of $V_{xy}^{(2)}$ with $(V_{xx}^{(2)})^2$ for two $(\nu, D)$ points biased near the CNP gap and moiré gap. Additionally, $V_{xy}^{(2)}$ switches sign when we simultaneously reverse the Hall voltage probes and current direction (Fig. 2e). These observations clearly demonstrate the second-order nature of the measured NLH voltage ($V_{xy}^{(2)}$).

Having established $V_{xy}^{(2)}$ as the NLH voltage, we now use $D$ as a parameter to study scaling between the normalized NLH voltage $V_{xy}^{(2)}/(V_{xx}^{(2)})^2$ and square of longitudinal conductivity ($\sigma_{xx}^2$). Such scaling can be used to quantify BCD, as discussed later. In Fig. 3a, we plot $V_{xy}^{(2)}/(V_{xx}^{(2)})^2$ (left axis) and $\sigma_{xx}^2$ (right axis) on $\nu$ values close to the CNP ($\nu = 0$) for regime II (c) and regime I (d). The fitting error bars are smaller than the size of the individual data points. e,f. Band structures of the K valley for two different values of the interlayer potential, namely, $\Delta = 38$ meV (e) and $\Delta = 25$ meV (f). The overlayed colour indicates the Berry curvature for the corresponding flat bands. The Berry curvature, and consequently the valley Chern numbers for the bands (indicated within the brackets), change across the topological transition. g,h. Corresponding variation in the calculated BCD as a function of energy $E$ with respect to the Fermi energy at $\Delta = 38$ meV (g) and $\Delta = 25$ meV (h). The coloured arrows are a visual guide to the sign change in the BCD peaks of each band. For example, the red arrows in g and h indicate the BCD peaks of the flat conduction band at $\Delta = 38$ and 25 meV, respectively. i. Colour-scale plot of the BCD as a function of $E$ and $\Delta$ at the conduction band side. The solid grey line marks the $\Delta$ value across which $Z_2$ of the flat conduction band changes together with a sign reversal in the BCD. The blue and orange dashed lines indicate the locations of line slices shown in g and h.
As one moves from regime I to regime II, the touching of the flat bands with the higher moiré dispersing bands leads to a change in the valley Chern numbers of the flat bands\(^9,10\), which in turn should be reflected in the change in sign of the BCD\(^3\).

To investigate the close connection of such topological transition with the BCD, we first experimentally analyse the scaling between \(V_{xy}^2/(V_{xx}^2)\) and \(\sigma_{xx}^2\) and later present a detailed calculation. In general, the NLH voltage incorporates contributions from the BCD, skew scattering and side jump. In the low-temperature limit, a normalized NLH voltage can be simplified as \(V_{xy}^2/(V_{xx}^2) = A\sigma_{xx}^2 + B\) (ref. 14). If \(\tau\) is the scattering time constant, slope \(A\) characterizes the contribution from the skew-scattering (\(\tau^2\)) process to the second-order NLH response\(^9\), whereas the BCD can be extracted from intercept \(B\) (refs. 17,18) (Supplementary Section VI). In Fig. 3b, we find linear scaling between \(V_{xy}^2/(V_{xx}^2)\) and \(\sigma_{xx}^2\) in both regime I and regime II. A fixed temperature assures that the contributions from skew scattering or side jump in the NLH effect are not tuned within the linear fitted regimes\(^9,10\). Interestingly, a near-zero slope in regime I suggests that the skew-scattering contribution is minimal when the flat bands are isolated from the remote moiré bands.

To distinguish the intrinsic BCD from other extrinsic contributions like side jump, we repeat the scaling analysis for different fillings close to the band edge (Extended Data Fig. 2). Figure 3c,d shows the extracted BCD from regime II and regime I. The drop in the extracted BCD away from the CNP (\(\nu = 0\)), consistent with the Berry curvature hotspot peaking at the band edge, suggests that the NLH effect we observe is dominated by the BCD. The most striking observation, central to our study, is the sign change in the BCD across the topological transition between regime I and regime II.

To theoretically verify the connection between this BCD sign change and topological transition, we calculate the band structure for two different values of interlayer potential \(\Delta\) (Fig. 3e,f). A change in the valley Chern number marks the topological transition. Consistently, the BCD changes sign (Fig. 3b,g) before and after the topological transition. The sign reversal of BCD can be further visualized (Fig. 3i), where a colour-scale plot of the BCD at the conduction band side is shown as a function of energy and \(\Delta\). We also note (Fig. 3e,f) that the Berry curvature changes sign, around the \(\Gamma\) point, across the topological transition. Thus, the NLH effect acts as a good probe to detect topological transitions associated with the change in the valley Chern numbers\(^9\).

We note that the experimentally measured BCD values (Fig. 3c,d) are about two orders of magnitude larger than the BCD observed in WTe\(_2\) (refs. 17,18). The scaling analysis using temperature as a parameter also gives a similar magnitude of BCD (Extended Data Fig. 3). A high BCD magnitude has been theoretically predicted in strained twisted systems\(^{11,12,30,31}\). The origin of high BCD in graphene-based moiré systems, in the vicinity of the CNP, can be understood using the model of strained twisted bilayer graphene as a tilted Dirac system\(^3\). In this model, BCD \(\propto t \lambda^3\), where \(t\) is the tilt parameter and \(\lambda\) is the moiré wavelength. Therefore, the BCD is expected to be higher in moiré materials compared with non-moiré materials like bilayer graphene (Supplementary Section V). Although our theory qualitatively captures the BCD physics of a topological transition, the experimentally observed BCD values (Fig. 3c,d) are about two orders of magnitude larger than our calculation (Fig. 3g–i). This quantitative difference can be understood due to the different magnitudes and nature of strain possible in a real sample (Supplementary Section II).

Finally, we examine the variation in NLH voltage \(V_{xy}^2\) at large displacement fields and, interestingly, observe a hysteretic response (Fig. 4a). Figure 4b shows the simultaneously measured \(V_{xx}\), which also reveals hysteresis with \(D\). The sense of hysteresis is doping dependent (Supplementary Section XII.4) and cannot be explained by charge traps in the dielectric. Supplementary Section XII shows the temperature effects, rate dependence and switching statistics of the hysteresis. Figure 4b (inset) shows the difference in \(V_{xx}\) for up and down sweeps. Intriguingly, the hysteresis is the maximum around \(D/\epsilon_0 = -0.23\) V nm\(^{-1}\) where a topological transition takes place (Fig. 3b). However, more studies are required for a full microscopic understanding.

Our experimental data suggest the existence of metastable states; the origin of these states can be due to two possible mechanisms. First, metastable polarization states in the system can arise from a difference in charge density across layers due to symmetry breaking in the device geometry (Methods). Second, flexoelectric coupling between the perpendicular electric field and strain gradient across the domain interfaces can lead to electric polarization in moiré systems\(^4\). Polarization from both possible mechanisms can lead to a
change in the strain profile that can be further pinned by defects; this can account for the hysteresis that we observe. Strain and polarization, through the effective electric field, modify the band structure and hence the values of $Y_{xx}$ and $Y_{yy}$.

Tunable BCD values, together with the coupling of BCD to hysteresis in the same platform (as we demonstrate using TDBG), may open new frontiers for memory devices where the readout is via the NLH effect. In general, probing topological transitions using electrical transport is challenging. Our experiment shows that the NLH effect can probe topological transitions. We demonstrate the idea by utilizing the electric-field-tunable band structure of a few-layer heterostructure, namely, TDBG. In three-dimensional topological systems, another parameter such as anisotropic strain or pressure can cause a topological transition. Theory predicts that such a transition (for example, BiTeI (ref. 14)), is accompanied by a BCD enhancement along with a sign change. Thus, our demonstration establishes a general pathway to detect topological transitions using the NLH effect applicable to three-dimensional systems, too.

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Methods
Device fabrication. We fabricate dual-gated TDBG devices. We have a metal top gate and SiO₂ (~280 nm)/Si back gate. Dual gates allow us to independently control the charge density (n) and perpendicular displacement field (D), where n = (C_{xx} V_n + C_{xy} V_{xy})/e and D = (C_{xx} V_n + C_{xy} V_{xy})/e. Here V_n (V_{xy}) is the back (top) gate capacitance and V_n (V_{xy}) is the voltage applied to the back (top) gate, respectively, and e is the electronic charge. To prepare the hexagonal boron nitride (hBN)/TDBG/hBN graphene stacks, we pre-cut bilayer graphene using a tapered optical fibre scalpel.14 The fabrication details are provided elsewhere.15 We determine twist angles using low-temperature electron transport measurement by using the relation n0 = 80π/3√3, where a = 0.246 nm is the lattice constant of graphene. Here n0, the carrier charge density corresponding to the full filling of the moiré band, is inferred from the location of resistance peaks on the n axis corresponding to the moiré gaps (Supplementary Section VII). The twist angle is additionally confirmed via magnetotransport measurements.

Measurement technique. We send current I through the DS360 ultralow-distortion function generator. The chosen frequency for all the data is 177 Hz, except for the case shown in Supplementary Fig. 11 (where we vary the frequency). Voltages V_{xy} and V_{xx} are measured using the SR830 lock-in amplifier in the first-harmonic and second-harmonic mode, respectively. In addition, to measure the d.c. voltage and second-harmonic mode, respectively. In addition, to measure the d.c. voltage generated due to the NLH effect, we use a Keithley 2182 (Supplementary Fig. 25) function generator. For the fillings of 0.23 V nm⁻¹, we see the manifest linear dependence. Using temperature as a parameter, we show a linear scaling using displacement field as a parameter; Fig. 3b) and displacement field D = −0.25 V nm⁻¹. In Extended Data Fig. 3a, we show the temperature dependence of the NLH voltage (blue-coloured data points) and longitudinal voltage V_{xy} (orange-coloured data points). We see that V_{xy} goes close to zero at ~20 K. In Extended Data Fig. 3b, we show the temperature dependence of the NLH voltage (black-coloured data points) and σ_x (red-coloured data points) using the data in Extended Data Fig. 3a. A decreasing σ_x with increasing temperature suggests that ν = 0.125 corresponds to π/8 moiré lobe in the flat band. In Extended Data Fig. 3c, we plot V_{xy} versus σ_x using temperature as a parameter and find similar linear dependence, as reported earlier,17 till T = 7 K. The temperature regime is less than the Bloch–Grüneisen temperature, ensuring that the other extrinsic contributions are not tuned in this temperature regime. A similar magnitude of σ_x in V_{xy} versus σ_x as in Fig. 3b suggests that BCD using temperature as a parameter is of similar magnitude as that obtained from the parametric scaling of D.

BCD and topological transition. To investigate the topological phase transition and associated sign reversal of BCD, we have followed a low-energy continuum model approach18 for twisted bilayer graphene and extended it to TDBG (Supplementary Section I). The perpendicular–electric field tunability of the electronic band structure has been included in the Hamiltonian by parameter Δ, which represents a constant potential gradient across the layers. The presence of finite strain in the fabricated TDBG sample breaks the C₃ symmetry (Fig. 1a), which causes a non-zero BCD. The uniaxial strain has been introduced into our model Hamiltonian as

\[
\mathcal{H} = e \left( -\cos \phi - \sin \phi \right) \left( -1 + \sin \phi \cos \phi \right)
\]

where a strain of magnitude e is applied along a direction that makes angle φ with the zigzag direction of graphene. Furthermore, r denotes Poisson’s ratio and is equal to ~0.16 for graphene. For our calculations, we have considered strain along the zigzag direction (φ = 0°).

In Extended Data Fig. 4, we have plotted BCD as a function of interlayer potential (Δ) and energy (E) at a fixed strain value of 0.1%. The butterfly structure of the evolution of BCD with the perpendicular electric field E constitutes one of the halves that is twisted by a small angle in the TDBG. The sign reversal of BCD near critical interlayer potential Δ = 34 meV indicates a topological transition. Extended Data Fig. 4a shows the y component of the BCD in the conduction band side (E > 0). Before the phase transition, at 25 and 30 meV, the red lobe signifies the negative BCD for the first conduction band, whereas the blue lobe represents a positive BCD for moiré conduction bands. The conduction band dispersions are shown in Extended Data Fig. 4b,c. The overlaid colour indicates the Berry curvature hotspots within the band. After the phase transition, at Δ = 38 and 43 meV, we observe a positive lobe of BCD for the first conduction band and a negative lobe for the higher conduction band. The corresponding dispersions are shown in Extended Data Fig. 4d,e. From the colour image of the Berry curvature, it is evident that in regime I (before transition), the valence (conduction) band has a negative (positive) Berry curvature hotspot, whereas this gets reversed in regime II (after transition).

Metastable states in hBN-encapsulated TDBG. To identify the metastable states that possibly cause the observed hysteretic, we first present a first-principles density functional theory analysis of a graphene–graphene–hBN trilayer, which constitutes one of the halves that is twisted by a small angle in the TDBG. Interestingly, the outer hBN monolayer breaks the sublattice symmetry, opening up a small gap at the Fermi level (Extended Data Fig. 5a), accompanied by weak layer asymmetry in the constitution of the frontier electronic states (bands of p orbitals) reflecting on an accumulation of a small electronic charge on one of the two graphene monolayers. This is expected from the lack of inversion or horizontal reflection symmetries in the trilayer, and our estimate of its polarization (along the z axis) is ~0.34 μC cm⁻². We analyse the effects of the perpendicular electric field on...
the TDBG in two steps, focusing first on the coupling of the field with the double bilayer graphene (twist angle, 0°) and then discussing the effect of twist in terms of variation in stacking between the double bilayer graphene layers. Using a rigid band model of frontier electronic states of double bilayer graphene (Supplementary Section XIII), we demonstrate that the electric field permits switching to two metastable states with opposite polarizations (Extended Data Fig. 5d) arising from the inversion of the frontier electronic states in one of the double bilayer graphene layers (Extended Data Fig. 5c). However, these states are symmetry equivalent and would not explain the hysteresis observed in the resistances of TDBG, which we argue to arise from two mechanisms: (1) inhomogeneous doping across the layers in the TDBG due to differences in the top and bottom doping as evident in our calculations of gated TDBG with a twist angle of 21.78° and (2) switchable ferroelectric polarization associated with the redistribution of regions with different stacking sequences (AA versus AB) across the twisted layers45.

Our calculations of the TDBG (twist angle, 21.78°) with a bottom gate reveals the development of polarization on doping with an estimate of 0.6 μC cm⁻² (Supplementary Fig. 24a). This is comparable to $P \approx 0.68 \mu \text{C} \text{cm}^{-2}$ of bilayered hBN (ref. 40) and larger than that ($P = -0.18 \mu \text{C} \text{cm}^{-2}$) arising from restructuring in terms of the stacking sequence26 in heterostructures. Thus, the observed hysteresis has possible contributions from inhomogeneous stacking as well as inhomogeneous layer-dependent carrier concentration.

Data availability
Source data are provided with this paper. The experimental data used in the figures of the main text are available at Zenodo47. Additional data related to this study are available from the corresponding authors upon reasonable request.

Code availability
The code that supports the findings of this study is available from the corresponding authors upon reasonable request.

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Author contributions
S.S., P.C.A. and L.D.V.S. fabricated the devices. S.S. and P.C.A. performed the measurements and analysed the data. A.C., K. Das and A.A. calculated the band structure and performed the BCD and Chern number calculations. K. Debnath and U.V.W. performed the polarization calculations. K.W. and T.T. grew the hBN crystals. S.S., P.C.A., A.A. and M.M.D. wrote the manuscript with inputs from all the authors. M.M.D. supervised the project.

Competing interests
The authors declare no competing interests.

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Extended Data Fig. 1 | Variation of longitudinal resistance with temperature. a–c, Variation of longitudinal resistance $R_{xx}$ with temperature $T$ for filling $\nu = 0.125$ (a), $\nu = 0$ (b) and $\nu = -4$ (c). The color of the line-plots indicates the corresponding displacement field.
Extended Data Fig. 2 | Scaling of normalized nonlinear Hall voltage $V_{xy}^2/(V_{xx})^2$ with the square of longitudinal conductivity ($\sigma_{xx}^2$) for different fillings $\nu$ with displacement field as parameter. a, d, g, j. The variation of nonlinear Hall voltage $V_{xy}^2$ (blue-colored data points corresponding to the left axis) and longitudinal voltage $V_{xx}$ (orange-colored data points corresponding to the right axis) as a function of the displacement field $D/\epsilon_0$ for four different fillings. b, e, h, k. The corresponding variation of normalized nonlinear Hall voltage $V_{xy}^2/(V_{xx})^2$ (black-colored data points corresponding to the left axis) and square of longitudinal conductivity $\sigma_{xx}^2$ (red-colored data points corresponding to the right axis) as a function of the displacement field $D/\epsilon_0$, extracted for the same fillings used in a, d, g, and j, respectively. c, f, i, l. The variation of normalized nonlinear Hall voltage $V_{xy}^2/(V_{xx})^2$ with square of longitudinal conductivity $\sigma_{xx}^2$ plotted parametrically as a function of the displacement field $D/\epsilon_0$, using b, e, h, and k, respectively. The displacement field value of data points in V nm$^{-1}$ is indicated by the color (color bar is shown in top right). The dashed green line and dashed blue line indicate fits to linear scaling in regime-I and regime-II respectively, used to extract BCD. The fillings shown here are $\nu = 0.112$ (a-c), 0.138 (d-f), 0.150 (g-i), and 0.175 (j-l). The light green background and light blue background correspond to regime-I and regime-II, respectively, as discussed in Fig. 3a of the main manuscript. The measurements were performed using a current of 100 nA with a frequency of 177 Hz at a temperature of 1.5 K.
Extended Data Fig. 3 | Scaling of normalized nonlinear Hall voltage $V_{xy}^2/(V_{xx})^2$ with square of longitudinal conductivity ($\sigma_{xx}^2$) with temperature as parameter. a, The variation of nonlinear Hall voltage $V_{xy}^2$ (blue-colored data points corresponding to the left axis) and longitudinal voltage $V_{xx}$ (orange-colored data points corresponding to the right axis) as a function of temperature $T$ for $\nu = 0.125$. b, The corresponding variation of normalized nonlinear Hall voltage $V_{xy}^2/(V_{xx})^2$ (black-colored data points corresponding to the left axis) and square of longitudinal conductivity $\sigma_{xx}^2$ (red-colored data points corresponding to the right axis) as a function of $T$, extracted for the same filling used in a. c, The variation of $V_{xy}^2/(V_{xx})^2$ with $\sigma_{xx}^2$ plotted parametrically as a function of $T$, using the results in b. The temperature value of data points in Kelvin is indicated by the color. The dashed line indicates a linear fit till 7 K.
Extended Data Fig. 4 | Evolution of Berry curvature dipole (BCD). a, Dependence of the y-component of BCD on the Energy ($E$) and inter-layer potential ($\Delta$) at the conduction band side. b, c, Energy dispersion along high symmetry k-paths for $\Delta = 25$ meV (b) and $\Delta = 30$ meV (c) before transition. d, e, Similar energy dispersion for $\Delta = 38$ meV (d) and $\Delta = 43$ meV (e) after transition. The color map shows the Berry curvature value for the flat bands.
Extended Data Fig. 5 | Metastable states and polarization in TDBG. **a**, Electronic structure of Graphene-Graphene-hBN shows a band gap of 26 meV at $K$ point. The inset shows the spatial distribution of the wave functions of bands labelled 2 and 3. **b**, Electric field ($E$) calculated from the slope of the average macroscopic potential of Graphene-Graphene-hBN in vacuum. **c**, Evolution and crossing of band 2 and 3 at $E = -0.0039$ V/Å and $E = 0.0039$ V/Å of upper and lower trilayer of hBN-TDBG-hBN as a function of electric field using our rigid band model. **d**, metastable states for (i) $E < -0.0039$ V/Å and (ii) $E > 0.0039$ V/Å, with nonzero polarization in hBN-TDBG-hBN that are accessible with the electric field.