Supplementary Figures

Supplementary Figure 1 | Evaluation of the STP measurements. a, Topography of a sample region containing an area of monolayer (ML) graphene separated by a substrate step and bilayer (BL) graphene. b, Thermovoltage map obtained for STP-measurements with no lateral applied voltage. c-d, STP-measurements with the indicated current density $j = \pm 12 \Lambda m^{-1}$ along the two horizontal directions. e-f, Separation of effects depending on the current direction from those independent of it. g, Section [dashed white line in (a)] through the topography in (a), the thermovoltage in (b) (dark blue) and (f) (light blue) as well as the voltage drop in (e). Since (f) and (b) are identical, the asymmetry with respect to current direction in (c) and (d) is caused by the thermovoltage and (e) is truly representative of the voltage drop in the sample area depicted. (Imaging conditions: $I_T = 0.2 \text{ nA}$, $V_{\text{bias}} = -30 \text{ mV}$).
Supplementary Figure 2 | Larger topography for Fig 2. On the left a monolayer graphene area is shown while the respective bilayer area is on the right. The periodic lattice originates from the 6x6-superlattice known from SiC-graphene ($I_T=0.35$ nA, $V_{bias}=-100$ mV).

Supplementary Figure 3 | Schematic of possible tip jumping artefacts. a, tunneling current contribution $I_T$ for a tip at the lower terrace of the step. b, At the step, the tip receives contributions to $I_T$ from different locations of the step. This also alters the results of a potentiometry measurement. c, Such artefacts are absent as soon as the tip reaches the upper terrace.
Supplementary Figure 4 | Resistor network model of the ML/BL-step. To model the shift caused by the increased interlayer resistance, we implemented a resistor network as depicted: A step resistance in the middle is surrounded by a monolayer and a bilayer side. Different resistance values for the monolayer, the step, for both layers of the bilayer and the interlayer-coupling are taken into account.

Supplementary Figure 5 | Results for the resistor network. a, Dependence on the ratio $\kappa$ between c-axis and in-plane resistance. (Further parameters: $\alpha = 10; j = 10 \text{ Am}^{-1}; \rho_{ML}=360 \Omega; \rho_{BL}=240 \Omega$) b, Potential drop for different ratios of resistances for the upper and the lower bilayer sheet $\alpha$. (Further parameters: $\kappa = 1 \cdot 10^5; j = 10 \text{ Am}^{-1}; \rho_{ML}=360 \Omega; \rho_{BL}=240 \Omega$)
Supplementary Figure 6 | Fit of the simulation to experimental data. a, Comparison between experimental data (red dots), the resistor network model (black solid line) and the analytical model (black dotted line) with the same parameters, both with $\kappa = 3 \cdot 10^3$. Additionally, results for $\kappa = 1 \cdot 10^3$ (blue dotted line) and $\kappa = 6 \cdot 10^3$ (orange dotted line) have been plotted. b, fit for a changed doping factor $\alpha = 18$ and $\kappa = 1.5 \cdot 10^3$ representing the best fit we obtained within the framework of this model. (Further parameters; $j = 10$ Am$^{-1}$; $\rho_{\text{ML}}=360$ $\Omega$; $\rho_{\text{BL}}=240$ $\Omega$)

Supplementary Table

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Supplementary Table 1 | Averaged values for the fit parameter in the step-function model for both ML/BL- and ML/ML-transition.
Supplementary Note 1

Evaluation of a voltage drop at ML/BL-junctions in the presence of thermovoltage. For low temperature STP data, the evaluation of the local voltage drop is influenced by the thermovoltage effect\textsuperscript{1,2}, a thermoelectric effect due to different temperatures of tip and sample. This quantity is obtained in the same STP measurement procedure as the local ECP (See Fig. 1a in the manuscript). In the following we demonstrate that it is possible to eliminate this contribution by simple mathematical operations on different voltage maps.

Tip and sample of a low-temperature STM are not necessarily at the same temperature. In this case the Seebeck-effect causes a finite current at equal ECP of tip and sample that will be canceled in the STP measurement by applying a difference between tip and sample potential of $V_{Th}(x,y)$. This voltage is only related to the temperature difference but not to any transport fields. In our given setup, the sample support is held at 6 K while the tip is only connected via thin silver wires to the helium bath. As a result, we obtain local variations in thermovoltage $V_{Th}$ of a few hundred $\mu$V. The thermovoltage effect in STM experiments was treated by Støvneng and Lipavský\textsuperscript{3} with the result that

$$V_{Th}(x,y) \propto \frac{\pi^2 k_B^2}{6 e^2} (T_T^2 - T_S^2) \frac{1}{\rho_S(E,x,y)} \left| \frac{d\rho_S(E,x,y)}{dE} \right|_{E=E_F}$$

where $T_T$ and $T_S$ are the temperature of the tip and sample, respectively. $\rho_S(E)$ is the local density of states of the sample. Hence, variations of $V_{Th}$ at the nanometer scale stem from the lateral variation of the logarithmic derivative of $\rho_S(E)$ at $E=E_F$. As a consequence the thermovoltage is sensitive to variations in the local density of states at the Fermi level comparable to scanning tunneling spectroscopy (STS)\textsuperscript{3}.

Supplementary Figure 1 demonstrates a large scale STP-analysis of the region shown in Fig. 1c in the manuscript, which consists of a monolayer-bilayer-transition and additionally a SiC-substrate step covered by graphene (ML/ML-junction). In Supplementary Figure 1b we plot the thermovoltage as the STP signal obtained without applying a lateral transport field. Here, a clear contrast between the monolayer and the bilayer is present due to the change in local density of states at the Fermi-energy. The maps in Supplementary Figures 1c and 1d show the potentiometry measurement with applied lateral voltage of $+10$ V/-10 V. For our sample geometry, this results in a (macroscopic) current density of $j_{mac} = \pm 12 \text{ Am}^{-1}$. It is apparent that the major effect in Supplementary Figure 1c and Supplementary Figure 1d is observed at the ML/BL and not at the ML/ML junction although the latter is structurally much more prominent (Supplementary Figure 1a). The data in Supplementary Figures 1c and 1d shows asymmetries with respect to the current direction for the voltage drop at the ML/BL-interface. However, it is crucial to realize that these maps contain not only the local response to the external applied transport field, but also a contribution of the local thermovoltage (Supplementary Figure 1b).
This prohibits a direct evaluation of the voltage drop from the data in Supplementary Figure 1c/1d. Since the thermovoltage does not depend on the current direction, its signal can be restored by averaging the data in Supplementary Figures 1c and 1d whereas the true transport field can be obtained as half the difference of the two maps. This is shown in Supplementary Figures 1e and 1f: The transport field in Supplementary Figure 1e now clearly shows distinct voltage drops across the layers and at the substrate steps whereas Supplementary Figure 1f only shows a contrast between ML and BL regions. The procedure, however, needs to be validated by comparing the restored thermovoltage signal with that measured in the absence of any current flow to exclude an asymmetric voltage drop with respect to current direction as has been reported recently by Clark et al. in the limit of high current densities \(^4\).

The restored thermovoltage in Supplementary Figure 1f shows the same contrasts as Supplementary Figure 1b, the thermovoltage without applied lateral voltage. That the two signals are identical is evidenced in the data sections shown in Supplementary Figure 1g. All the fine features are reproduced. We can therefore be certain, that the ML/BL boundary scatters electrons with reversed current path identically.

To check the validity of this procedure, we treat the thermovoltage in a more detailed mathematical description in the following.

Let \( V_{STP}^0(x) = V_{Th}(x) \) be the measured STP signal with no lateral voltage applied, i.e. the pure thermovoltage. For a finite current applied, we then measure for forward and reverse current direction:

\[
V_{STP}^\rightarrow(x) = \mu_{ECP}(x)/e + \epsilon \cdot V_{Th}(x) \quad \text{and} \quad V_{STP}^\leftarrow(x) = \mu_{ECP}(x)/e - \epsilon \cdot V_{Th}(x) \tag{2}
\]

We introduced a constant scaling factor \( \epsilon = \epsilon(|I|) \) that scales the thermovoltage due to possible resistive heating of the sample. Note that even for symmetric transport properties \( [\mu_{ECP}(x) = -\mu_{ECP}(x)] \) \( V_{STP}(x) \) does not show the same behavior with respect to current reversal. It is obvious that thermovoltage and ECP can be retrieved by adding or subtracting the measured maps \( V_{STP}^\rightarrow(x) \) and \( V_{STP}^\leftarrow(x) \) from each other, i.e. we can now obtain the pure transport field by

\[
\frac{1}{2}[V_{STP}^\rightarrow(x)-V_{STP}^\leftarrow(x)] = \frac{1}{2\epsilon} [\mu_{ECP}(x)-\mu_{ECP}(x)] = \mu_{ECP}(x)/e \tag{3}
\]

And we can restore the thermovoltage by

\[
V_{Th}^{\text{restored}}(x) = \frac{1}{2}[V_{STP}^\rightarrow(x)+V_{STP}^\leftarrow(x)] = \epsilon \cdot V_{Th}(x) \tag{4}
\]
This evaluation method works of course only if the transport field for both directions is purely symmetric. To test the transport field at the ML/BL boundary for a possible asymmetric voltage drop (i.e., the voltage drop caused by electrons traversing from the monolayer to the bilayer is different than for the opposite direction), we assume an asymmetry of the form:

$$\mu_{\text{ECP}}(x) = -\mu_{\text{ECP}}(x) + \delta \Theta(x)$$  \hspace{1cm} (5)

Where $\Theta(x)$ is a step function at the position of the junction. Then, we would obtain for the transport field and thermovoltage

$$V_{\text{STP}}^{\text{restored}}(x) = \frac{1}{2} [V_{\text{STP}}^{\leftarrow}(x) - V_{\text{STP}}^{\rightarrow}(x)] = \mu_{\text{ECP}}(x)/e - \delta \Theta(x)/e$$  \hspace{1cm} (6)

$$V_{\text{Th}}^{\text{restored}}(x) = \frac{1}{2} [V_{\text{STP}}^{\leftarrow}(x) + V_{\text{STP}}^{\rightarrow}(x)] = e \cdot [V_{\text{Th}}(x) + \delta \Theta(x)/e]$$  \hspace{1cm} (7)

So while $V_{\text{ECP}}^{\text{restored}}(x)$ will only show an enlarged voltage drop at the ML/BL junction due to $\delta \Theta(x)$, only if the restored thermovoltage $V_{\text{Th}}^{\text{restored}}(x)$ is compared to $V_{\text{Th}}^{\text{restored}}(x)$ it can be revealed whether an asymmetric behavior of current transport across the ML/BL junction is present. This is not the case in our experiments as shown in Supplementary Figure 1g: measured and restored thermovoltage are identical. This is not only true for the difference between ML and BL signals but even most of the fine features are reproduced. The residual deviations are caused by the inherent difficulty to exactly align two STM traces measured at different times due to piezo nonlinearities.

We can therefore be certain that our measurements do not show any asymmetry of transport properties of the ML/BL junction with respect to the direction of current transport across. This is in agreement with most other reports\textsuperscript{5,6}. Recent studies by Clark et al. that report an asymmetry caused by a Friedel oscillation-induced energy gap claim this exclusively in a high voltage/current density range significantly higher than ours\textsuperscript{4}.

Both ML/BL-steps in Supplementary Figure 1f (the left and the right end of the bilayer graphene island) yield similar voltage drops of $147(5) \mu V / 161(5) \mu V$ resulting in a step resistance of $12(1) \Omega \mu m / 13(1) \Omega \mu m$ (using the local slopes and a macroscopic current density of $j_{\text{m}} = \pm 12 \text{ Am}^{-1}$).
Supplementary Note 2

Exclusion of tip jumping artefacts. For the interpretation of the data, it is important to exclude the possibility of tip jumping artefacts. These effects stem from blunt tips or multiple tips and can lead to measured voltage drops that deviate from the actual electrochemical potential at the position of the tip. This appears usually in topographically rough areas as e.g. steps, wrinkles and grain boundaries and is demonstrated in Supplementary Figure 3. Far away from the step (Supplementary Figure 3a), where the topography is flat, the tunneling current is dominated by an area that is directly below the tip. This changes when the tip is getting closer towards the step on the lower terrace (Supplementary Figure 3b). Here, contributions from the step affect not only the topography measurement but also a potentiometry measurement. This leads to an incorrect electrochemical potential at this point. Fortunately, the shift of the potential we observe in the manuscript takes place in the bilayer, which is the higher terrace. As can be seen from Supplementary Figure 3c, as soon as the tip reaches the upper layer, the contribution of the step and the lower layer can be neglected, since their contribution decays exponentially with distance. As can be seen from Figure 3c in the manuscript, we first see the topographic onset of the bilayer and then the gradual change of the potential. Therefore, we can exclude tip jumping artefacts to alter the ECP from the very start of the bilayer.

A second possible artefact can originate from multiple tips, but this would also be visible in the topographies, especially at the step.

Supplementary Note 3

Fitting procedure for the lateral position of the voltage drop. To evaluate the lateral shift of the potential with respect to the topographic step, both are fitted to step functions.

\[ V_{\text{STP}}(x) = \Delta V_{\text{STP}} \cdot \left( 1 + e^{\frac{x-x_0}{L_{\text{av}}}} \right)^{-1} + \Delta V_{\text{offset}} \]  \hspace{1cm} (8)

\[ h(x) = \Delta z \cdot \left( 1 + e^{\frac{x-x_0}{L_{\text{az}}}} \right)^{-1} + \Delta z_{\text{offset}} \]  \hspace{1cm} (9)

Here, \( x_0 \) is the absolute position of the transition which we defined at 50% of its height (FWHM-point). \( V_{\text{STP}} \) and \( \Delta z \) are the amplitudes, \( L_{\Delta z} \) and \( L_{\Delta V} \) describe the spatial extension of the topography and the drop in the ECP, respectively. This fitting was done for all lines of an STP-measurement. For each fitted line the average of 6 data sections was used as input to decrease the influence of fluctuations. All steps have been analyzed in this manner, all with a spatial resolution of \( \leq 0.5 \text{ nm} \). \( L_{\Delta V}, L_{\Delta z} \) and the lateral offset \( \Delta x = x_{0, \text{STP}} - x_{0, h} \) averaged for the two types of investigated
junctions are given in Supplementary Table 1. As already mentioned in the manuscript, the average lateral offset \(\langle \Delta x \rangle\) of the potential is significantly different from zero for the ML/BL-transition only. Also the spatial extension \(\langle L \rangle_{\Delta V}\) of this transition is wider than for the ML/ML-case leading to the smooth increase in potential as shown in the manuscript (see Fig. 2c).

**Supplementary Note 4**

**Simulation of the shifted voltage drop.** The lateral extended potential shift of the voltage drop is first described by a resistor network. In Supplementary Figure 4 the equivalent circuit diagram is shown. We employ 5 different types of resistors: for the monolayer \(R_{ML}\), for the step \(R_{Step}\), the upper bilayer sheet \(R_{BL\uparrow}\), the lower bilayer sheet \(R_{BL\downarrow}\) and the interlayer resistance \(R_\perp\) between the bilayer sheets.

The values for \(R_{ML}\) and \(R_{BL} = \frac{1}{\frac{1}{R_{BL\uparrow}} + \frac{1}{R_{BL\downarrow}}}\) are obtained by fits to the experimental slope of the sheets. Here, we use sheet resistances of \(\rho_{ML} = 360\ \Omega\) and \(\rho_{BL} = 240\ \Omega\) obtained from the data in Fig. 2 in the manuscript (In that figure the voltage drop within the bilayer is not well resolved due to the small length scale. The value of 240\ \Omega\ is deduced from observations on a larger scale, e.g. Fig. 1e in the manuscript). This is in good agreement with other reports.\(^5,8\) However, as a result from our own measurements, we should state that these values can vary significantly on a local scale. Applying this model the resistance is simply given by

\[
R_{ML} = \rho_{ML} \cdot \frac{L}{W} \quad R_{BL} = \rho_{BL} \cdot \frac{L}{W} \tag{10}
\]

Here, \(L\) is the length of a segment between two resistors and \(W\) the width of the system. Since all resistances scale with \(L/W\), its choice does not influence the shape of the potential. The n-doping of epitaxial graphene on SiC is induced by the charged buffer layer. As a consequence the charge carrier concentration and hence the conductivity\(^9\) of the upper bilayer sheet are decreased by a factor of 10 as shown by photoemission studies\(^10,11\). Consequently, we assume for the resistances

\[
R_{BL\uparrow} = (\alpha + 1) \cdot R_{BL} \cdot \frac{L}{W} \quad R_{BL\downarrow} = \frac{1}{\alpha} \cdot R_{BL} \cdot \frac{L}{W} \quad R_{BL\uparrow}^{-1} + R_{BL\downarrow}^{-1} = R_{BL}^{-1} \tag{11}
\]

With the doping factor \(\alpha = \rho_{BL\uparrow}/\rho_{BL\downarrow}\). Here we use for now a decrease by \(\alpha = 10\) as stated above. To describe the voltage drop directly at the step we use the single resistance \(R_{Step}\) which is caused by the detachment of the layer. It can be calculated from the line resistance of the step \(\rho_{Step}\) by

\[
R_{Step} = \frac{\rho_{Step}}{W} \tag{12}
\]

Here, we used \(\rho_{Step} = 3\ \Omega \mu m\) which is comparable to the resistance of a ML/ML-step of that height in agreement with Ji et al.\(^5\) and our own results.

The last parameter in the simulation is the interlayer resistance \(R_\perp\) which we describe in terms of the ratio \(\kappa\) with respect to the bilayer sheet resistance:

\[
\rho_\perp = \kappa \cdot \rho_{BL,\text{Bulk}} \tag{13}
\]
By introducing the bulk resistivity of the bilayer sheet \( \rho_{\text{BL,Bulk}} = \rho_{\text{BL}} \cdot d \), with the thickness of a graphene/graphite layer \( d = 0.34 \text{ nm} \), we can write the interlayer resistance in terms of

\[
R_L = \rho_{L} \cdot \frac{d}{W \cdot L} = \kappa \cdot \rho_{\text{BL}} \cdot \frac{d^2}{W \cdot L}
\]  

(14)

From literature the ratio between c-axis and in-plane transport for graphite is found to be between \( 10^2-10^6 \). A theoretical treatment by Wallace\(^{13} \) yields a factor of \( 10^2-10^4 \) depending on temperature. For epitaxial graphene on ruthenium Sutter et al. found an increase of \( 10^3 \) of the resistance for a contact distance of 10 \( \mu \text{m} \) depending on whether a ML/BL-step (and consequently interlayer transport) is present or not\(^{14} \).

We performed simulations for different values of the ratio \( \kappa \). In Supplementary Figure 5a we show the results of this simulation. The best fit with the experimental data was obtained by \( \approx 1 \cdot 10^3 \) which fits very well to the literature values. In Supplementary Figure 5b we also show the dependence of the potential drop on the ratio between \( R_{\text{BL}\uparrow} \) and \( R_{\text{BL}\downarrow} \) to demonstrate that the inequivalence induced by different doping has an essential impact on the extended potential shift.

All shown potential drops at the step are calculated for the potential of the upper sheet. The potential at positions in the vicinity of the step differs from the lower sheet due to the high interlayer resistance (This is also indicated in Fig. 4d in the manuscript). However, this is still in agreement with the experiment, since the potential of the surface, i.e. the upper sheet, is the one mainly mapped by the STP.

In addition, Wang and Beasley suggested an analytical model\(^{15} \) for scanning probe experiments at the contact region between two materials. This model can be applied if the upper bilayer is considered as a separate material with sheet resistance \( \rho_{\text{BL}\uparrow} \), that is in contact with the lower bilayer with sheet resistance \( \rho_{\text{BL}\downarrow} \). The interlayer resistance can then be considered as the contact resistance \( R_C \). The voltage drop is then given by

\[
V_{\text{ML}} = -j \cdot \rho_{\text{ML}} \cdot x
\]  

(15)

\[
V_{\text{BL}\uparrow} = -j \cdot R_C \left[ \frac{l^3}{l_{\text{BL}\uparrow}^3} \left( 1 - e^{-x/L} \right) + \frac{l^2}{l_{\text{BL}\uparrow}^2} \cdot x \right]
\]  

(16)

\[
V_{\text{BL}\downarrow} = -j \cdot R_C \left[ \frac{l^3}{l_{\text{BL}\downarrow}^3} + \frac{l^3}{l_{\text{BL}\downarrow}^3} e^{-x/L} + \frac{l^2}{l_{\text{BL}\downarrow}^2} \cdot x \right]
\]  

(17)

With the current density \( j \) and the transfer lengths

\[
l_{\text{BL}\uparrow} = \sqrt{\rho_{\text{BL}\uparrow}/R_C} \quad l_{\text{BL}\downarrow} = \sqrt{\rho_{\text{BL}\downarrow}/R_C} \quad L = \sqrt{\frac{l_{\text{BL}\uparrow} \cdot l_{\text{BL}\downarrow}}{l_{\text{BL}\uparrow}^2 + l_{\text{BL}\downarrow}^2}}
\]  

(18)

Supplementary Figure 6a shows the results for this analytical model (black dotted line) together with the results of the resistor network model (black solid line) with the same parameters as used above. The slight deviation of the two is caused by the step resistance that cannot be included easily into the analytical model.

This is the main difference between both approaches. While the resistor network is flexible in modelling the voltage drop, the analytical model is very intuitive and easier
to handle. In the limit of small step resistance contribution they lead to the same results. We also plotted the experimental results from Fig. 2c in the manuscript. Besides, more analytical results have been plotted for different values for the ratio $\kappa$. The fit of the black curve has been obtained with

$$\alpha = 10; \quad \kappa = 3 \cdot 10^3; \quad j = 10 \text{ Am}^{-1}; \quad \rho_{\text{ML}}=360 \Omega; \quad \rho_{\text{BL}}=240 \Omega;$$

leading to

$$\rho_{\text{BL\uparrow}} = (\alpha+1)\rho_{\text{BL}} = 2640 \Omega; \quad \rho_{\text{BL\downarrow}} = \frac{(\alpha+1)}{\alpha}\rho_{\text{BL}} = 264 \Omega$$

$$R_C = \kappa \cdot \rho_{\text{BL}} \cdot d^2 = 8.3 \cdot 10^{-10} \Omega \text{ cm}^2$$

Moreover, the transfer lengths are

$$l_{\text{BL\uparrow}} = 5.9 \text{ nm} \quad l_{\text{BL\downarrow}} = 17.7 \text{ nm} \quad L = 5.6 \text{ nm}$$

We find, while these parameters already yield an adequate description of the effect of the extended and shifted voltage drop, the fit to the experimental data can even be improved by tuning the doping factor $\alpha$. For $\alpha = 18$ and $\kappa = 1.5 \cdot 10^3$ we obtain the curve shown in Supplementary Figure 6b. Taking this result seriously, we can conclude that the change in doping concentration deviates by more than a factor of 10 between two layers, at least at the ML/BL-interface. The best fit we obtain for

$$\alpha = 18; \quad \kappa = 1.5 \cdot 10^3; \quad j = 10 \text{ Am}^{-1}; \quad \rho_{\text{ML}}=360 \Omega; \quad \rho_{\text{BL}}=240 \Omega;$$

Leading to the following values

$$\rho_{\text{BL\uparrow}} = (\alpha+1)\rho_{\text{BL}} = 3800 \Omega; \quad \rho_{\text{BL\downarrow}} = \frac{(\alpha+1)}{\alpha}\rho_{\text{BL}} = 211 \Omega$$

$$R_C = \kappa \cdot \rho_{\text{BL}} \cdot d^2 = 4.2 \cdot 10^{-10} \Omega \text{ cm}^2$$

Moreover, the transfer lengths are

$$l_{\text{BL\uparrow}} = 3.1 \text{ nm} \quad l_{\text{BL\downarrow}} = 12.8 \text{ nm} \quad L = 3.0 \text{ nm}$$

This fit is also shown in Fig. 2c in the manuscript.

**Supplementary References**


