Electronic Raman Scattering in Twistronic Few-Layer Graphene

A. García-Ruiz,1,2 J. J. P. Thompson,1,3 M. Mucha-Kruczyński,1,4,* and V. I. Fal’ko2,5

1Department of Physics, University of Bath, Claverton Down, BA2 7AY, United Kingdom
2National Graphene Institute, University of Manchester, Booth St E, Manchester, M13 9PL, United Kingdom
3Department of Physics, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
4Centre for Nanoscience and Nanotechnology, University of Bath, Claverton Down, BA2 7AY, United Kingdom
5Department of Physics, University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom

We study electronic contribution to the Raman scattering of two- to four-layer graphene with the top layer twisted by a small angle, \( \theta < 2^\circ \), relatively to the 2D crystal underneath. We find that the Raman spectrum features two peaks produced by van Hove singularities in moiré minibands characteristic for twistronic graphene, one related to direct hybridization of Dirac states, and the other resulting from band folding caused by moiré superlattice. The positions of both peaks strongly depend on the twist angle, so that their detection can be used for non-invasive measurements of twist angle, even in the hBN-encapsulated structures.

PACS numbers:

Twisted bilayer graphene is a van der Waals heterostructure where the relative twist between the crystallographic directions of constituent atomic planes alters its electronic properties [1, 2]. Here, a small-angle twist produces a long-period moiré pattern which generates minibands for electrons with a small moiré Brillouin zone (mBZ). The minibands and gaps between them strongly depend on twist angle \( \theta \), leading to correlated electronic states, including Mott insulator and superconductivity, for a magic angle, \( \theta \approx 1.1^\circ \) [1–11], where the lowest miniband appears to be almost flat. Narrow minibands also appear in \((1 + 2) \) [12, 13] and \((1 + 1 + 1) \) [14] tri-layers. Theoretical studies predict that appearance of correlated electronic phases is generic for a large family of ‘twistronic’ graphene stacks [15–21], highlighting the need to expand the characterization toolbox of fast and non-invasive methods for the twist angle in such structures.

Here, we show that this can be achieved using Raman spectroscopy of electronic excitations. Raman scattering with phonons has stood out as a powerful, non-invasive method to inspect carbon materials [22], providing information about defects, doping, strain and the number of layers in the film. Twist of graphene layers was shown to lead to resonant enhancement of the \( G \) peak [23, 24], the width and position of the 2D peak [25], as well as of processes involving phonons folded onto the mBZ [26–28] and layer breathing and shear modes [29, 30], however, with a limited accuracy in determining the twist angle. Below, we demonstrate that Raman spectroscopy of the interband electronic excitations (ERS) [31–42] can be used to detect twist-angle-dependent features in the electronic spectrum of material. Below, we study the electronic minibands and electronic contributions to the Raman spectra for \((1 + N)\)-layer graphene stacks in which the top layer is twisted by a small angle \( 0.8^\circ < \theta < 2^\circ \) with respect to \( N = 1, 2, 3 \) layers underneath, as shown in Fig. 1(a). We find that ERS is formed by transitions from the \( n \)-th valence to the \( n \)-th conduction moiré superlattice (mSL) miniband (selection rules complementary to those for optical absorption [43, 44]) and features two spectral peaks. One, at a lower Raman shift, is caused by the resonant hybridization of electronic states of the twisted monolayer and the underlying \( N \)-layer stack [45, 46]. Another, higher-energy peak is due to the anti-crossing of bands, backfolded by mSL. Both peaks are related to van Hove singularities in the mSL minibands. We trace the peaks positions as a function of twist angle. Below, we study the electronic minibands and electronic contributions to the Raman spectra for \((1 + N)\)-layer graphene stacks in which the top layer is twisted by a small angle \( 0.8^\circ < \theta < 2^\circ \) with respect to \( N = 1, 2, 3 \) layers underneath, as shown in Fig. 1(a). We find that ERS is formed by transitions from the \( n \)-th valence to the \( n \)-th conduction moiré superlattice (mSL) miniband (selection rules complementary to those for optical absorption [43, 44]) and features two spectral peaks. One, at a lower Raman shift, is caused by the resonant hybridization of electronic states of the twisted monolayer and the underlying \( N \)-layer stack [45, 46]. Another, higher-energy peak is due to the anti-crossing of bands, backfolded by mSL. Both peaks are related to van Hove singularities in the mSL minibands. We trace the peaks positions as a function of twist angle.

FIG. 1: (a) Pictorial representation of \((1 + N)\) twistronic graphene. The red and blue balls correspond to the two different sub-lattice sites in each graphene layer and green ellipse represents a dimer bonding leading to direct interlayer coupling. (b) Brillouin zones of the \( N \)-layer stack (dashed black line) and the top graphene (dashed purple line) with corners \( K \) and \( K' \), respectively, as well as the effective moiré Brillouin zone (solid black line). (c) Feynman diagrams for the scattering amplitudes \( R \) contributing to the electronic Raman features discussed in this paper.
the twist angle and estimate their quantum efficiency, $I \sim 10^{-11}$, to be in the measurable range [31–37].

To model twistronic graphene, we use a hybrid $k \cdot p$ theory-tight-binding model, where we describe electrons' states in each flake using the $k \cdot p$ expansion around $\pm K$ and $\pm K'$ Brillouin zone corners [see Fig. 1(b)] and the interlayer hybridization using tunneling Hamiltonian [46, 47]. The Hamiltonian $\hat{H}_{1+NX}$ for an electron in a $(1 + NX)$ structure ($X = B$ for Bernal or $X = R$ for rhombohedral stacking of the $N \equiv 3$ crystal) and with momentum $p = (p_x, p_y)$ measured from the centre of the valley $\pm K$ in the $N$-layer bottom flake is

$$
\hat{H}_{1+NX} = \begin{bmatrix}
\hat{H}_{1,\theta} & \hat{T}_\theta \\
\hat{T}_\theta^\dagger & \hat{H}_{NX}
\end{bmatrix}
\begin{bmatrix}
\hat{0}_{2 \times (N-1)} \\
\hat{0}_{2 \times (N-1) \times 2}
\end{bmatrix}.
$$

(1)

Here, $K = \frac{2\pi}{a}(1,0)$, $a$ is the graphene lattice constant, $K' = \hat{R}_\theta K$ [$\hat{R}_\theta$ clockwise rotates by angle $\theta$, see Fig. 1(b)], $\hat{0}_{n \times m}$ is the $n \times m$ matrix of zeros, and $\hat{H}_{1,\theta}$ and $\hat{H}_{NX}$ account for rotated monolayer graphene and a perfectly stacked $N$-layer crystal, respectively:

$$
\hat{H}_{1,\theta} = \gamma_3 e^{i\frac{\pi}{2} \sigma_z} \cdot (p - \hbar \Delta K) e^{-i\frac{\pi}{2} \sigma_z},
$$

$$
\hat{H}_2 = \begin{bmatrix}
\hat{H}_1 & \hat{T} \\
\hat{T}_\dagger & \hat{H}_1
\end{bmatrix},
\hat{H}_{3X} = \begin{bmatrix}
\hat{H}_1 & \hat{T}_X \\
\hat{T}_X^\dagger & \hat{H}_1
\end{bmatrix},
\hat{H}_{NX} = \begin{bmatrix}
\hat{H}_X & \hat{0}_{2 \times 2} \\
\hat{0}_{2 \times 2} & \hat{H}_X
\end{bmatrix}.
$$

(2)

In $\hat{H}_1(\theta)$, $\sigma = (\sigma_x, \sigma_y)$, with $\sigma_x, \sigma_y, \sigma_z$ the Pauli matrices; $\Delta K = K' - K$ is a mismatch between Brillouin zone corners (valleys) in the top and bottom crystals and $v$ is the monolayer Dirac velocity. The interlayer coupling block in $\hat{H}_2$ in Eq. (2) is

$$
\hat{T} = \begin{bmatrix}
-v_3 \hat{\pi}^\dagger & v_3 \hat{\pi} \\
\gamma_1 & -v_4 \hat{\pi}^\dagger
\end{bmatrix},
$$

where $\hat{\pi} = p_x + ip_y$, $\gamma_1 = 0.39$ eV is the 'direct' interlayer coupling between the dimer sites, see Fig. 1(a), and $v_3$ and $v_4$ are velocities related to interlayer skew couplings $\gamma_3 \approx 0.3$ eV and $\gamma_4 \approx 0.04$ eV [48]. In trilayer (and $N > 3$) crystals, $\hat{T}_B = \hat{T}_1^\dagger$ but $\hat{T}_R = \hat{T}$. Finally, the block $\hat{\bar{T}}(\theta)$ in Eq. (1) captures the interlayer coupling between
the $N$-layer crystal and the twisted top monolayer and we write it following previous works [46, 47],
\[
\hat{T}_\theta = t \left( \hat{T}_1 + \hat{T}_2 e^{i G_1 \cdot r} + \hat{T}_3 e^{i G_2 \cdot r} \right),
\]
\[
\hat{T}_{n+1} = \hat{I}_2 + \cos \left( \frac{2\pi n}{3} \right) \sigma_x + \xi \sin \left( \frac{2\pi n}{3} \right) \sigma_y.
\]
Here, $G_1 = \sqrt{3} \hat{R}_{2\pi/3} \Delta K$ and $G_2 = \sqrt{3} \hat{R}_{-2\pi/3} \Delta K$, $\xi = \pm$ selects the valley $\xi \mathbf{K}$ and we use $t \approx 110$ meV [47] for interlayer coupling ($I_d$ is the $d \times d$ unit matrix). $\hat{T}_\theta$ in Eq. (3) is responsible for mSL effects and defines the hexagonal mBZ marked in Fig. 1(b).

In the electronic Raman scattering (ERS), photon of energy $\Omega$ arrives at the sample (here, we assume normal incidence of light) and scatters to a photon with energy $\Omega' = \Omega - \omega$, leaving behind an electron-hole pair with energy $\omega$. In contrast to classical plasmas, where the amplitude of such process is controlled by contact interaction ($A_A \cdot \partial p \partial r A'$, $A$ and $A'$ are the vector potentials of the incoming and outgoing light, respectively), in graphene, the dominating contribution comes from a two-step process, described by the Feynman diagrams shown in Fig. 1(c). It corresponds to absorption (emission) of a photon with energy $\Omega$ ($\Omega'$) transferring an electron with momentum $p$ from an occupied state in the valence band into a virtual intermediate state (energy is not conserved at this stage), followed by emission (absorption) of a second photon with energy $\Omega'$ ($\Omega$) [31, 32], with an amplitude [37]
\[
R = \frac{i(e\hbar v)^2}{\epsilon_0 \Omega^2} (l \times l)_z \hat{I}_{N+1} \otimes \sigma_z.
\]
Here, the main contribution to the Raman signal comes from $n^- \rightarrow n^+$ minisubband transitions, where $n^s$ denotes the $n$-th miniband on the valence ($s = -1$) or conduction ($s = 1$) side. This ERS signal can be filtered out from the phonon $G$-line by selecting the cross-polarized component of the Raman signal. The overall lineshape $g(\omega)$ of inelastic photon scattering with Raman shift, $\omega = \Omega - \Omega'$, is described using Fermi’s golden rule,
\[
g(\omega) = \frac{1}{c} \int \frac{d\mathbf{q}'}{(2\pi \hbar)^3} w(\omega) \delta(\Omega' - c|\mathbf{q}'|) = \frac{\Omega^2}{(2\pi \hbar)^3 c^4} w(\omega),
\]
\[
w(\omega) = \frac{2}{\pi \hbar^3} \sum_{n^s,m^s} \int \frac{d\mathbf{p}}{(2\pi \hbar)^3} \left| \langle \mathbf{p}, m^s | R | \mathbf{p}, n^s \rangle \right|^2
\]
\[
\times f_{p,n^s}(1 - f_{p,m^s}) \delta(\epsilon_{p,m^s} - \epsilon_{p,n^s} - \omega),
\]
where $f_{p,n^s}$ is the occupation factor of a state $| \mathbf{p}, n^s \rangle$ with momentum $p$ and energy $\epsilon_{p,n^s}$ in the band $n^s$.

In Fig. 2 (r.h.s.), we present the ERS intensity map for a $(1 + 1)$ twisted bilayer graphene in a twist angle range $0.8^\circ < \theta < 2^\circ$, neglecting its atomic reconstruction [49]. Two bright features stand out in this plot, corresponding to transitions between the minibands $1^- \rightarrow 1^+$ and $2^- \rightarrow 2^+$. For two selected cuts at $\theta = 1.8^\circ$ and $\theta = 1.1^\circ$, the peaks come from transitions indicated by arrows in the corresponding minibands plots. The first peak, $1^- \rightarrow 1^+$, is due to transitions from or to flat regions of electronic dispersion resulting from hybridization of the Dirac cones of the two layers (the Dirac points can still be identified in the dispersion for $\theta = 1.8^\circ$ as touching points of the minibands shown in red), which are responsible for a van Hove singularity (vHS) in the density of states [45, 46]. This vHS can be regarded as a direct evidence of interlayer hybridization of the Dirac band in graphene monolayers. As the twist angle is decreased,
FIG. 4: Comparison of ERS intensity maps for (1+3B), (a), and (1+3R), (b), twisted tetralayer graphenes as well as miniband structures for $\theta = 1.1^\circ$. The green dashed lines in the ERS maps indicate twist angles $\theta = 1.8^\circ$ and $\theta = 1.1^\circ$ and the green solid lines show the corresponding Raman spectra.

this ERS peak moves to lower energies. The second peak, $2^- \rightarrow 2^+$, is due to the transitions between the flat regions of the second valence and conduction minibands, indicated by orange arrows in the miniband structure for $\theta = 1.1^\circ$, with the overall intensity provided by the mBZ section painted in yellow in the left-most inset below the ERS map. The other two panels show the real-space distribution of the saddle point states across the moiré supercell in the top and bottom monolayers. For the $2^- \rightarrow 2^+$ peak, both the initial and final states are close to vHs, while for the $1^- \rightarrow 1^+$ peak this is the case only for either the initial or final state. Hence, for the same twist angle, the $2^- \rightarrow 2^+$ feature is larger than $1^- \rightarrow 1^+$. In Fig. 3, we show the ERS intensity map for (1+2) twistronic graphene and an exemplary miniband structure for $\theta = 1.1^\circ$. Similarly to (1+1) graphene, the dominant contributions come from the $1^- \rightarrow 1^+$ and $2^- \rightarrow 2^+$ electronic transitions. The two peaks also have the same origins: the first one is due to direct hybridization of the monolayer and bilayer states between the valleys $K'$ and $K$ while the second is formed by states backfolded by moiré superlattice. However, for a given twist angle, the peaks appear at lower Raman shifts than in the (1+1) structure. This is because the unperturbed dispersion in bilayer is flatter than in a monolayer – as a consequence, the anti-crossings and hence the vHs form at lower energies as compared to the (1+1) stack. To the right of the miniband spectrum, we show (in yellow) the regions of the mBZ which contribute to the $2^- \rightarrow 2^+$ ERS peak.

In Fig. 4, we plot ERS maps of two monolayer-on-trilayer structures, (1+3B) and (1+3R), together with exemplary miniband dispersions for $\theta = 1.1^\circ$. Bernal-stacked trilayer graphene, Fig. 4(a), hosts both a bilayer- and monolayer-like low-energy bands which hybridize with the top monolayer states and produce multiple overlapping contributions with a structure less pronounced than in both the (1+1) and (1+2) systems. In contrast, rhombohedral trilayers only host one low-energy
band, with a cubic dispersion in the vicinity of the valley centre [51]. This low-energy band is localised on the top and bottom surfaces of the crystal and is significantly affected by mSL produced by the top layer twist, leading to a pair of clear spectral features, Fig. 4(b), as in (1 + 1) and (1 + 2) twistronic graphene.

Overall, studies of electronic Raman scattering in (1 + N) twistronic graphene (for N = 1, 2, 3) identify two clear features in the Raman spectrum, corresponding to electron-hole excitations involving van Hove singularities of moiré superlattice minibands, with the Raman shift dependent on the twist angle between the layers. Currently, accurate determination of the twist angle, especially in the small-angle regime, requires time-consuming microscopic investigations of the moiré pattern or magneto-transport measurements to determine the size of the mBZ. We suggest that, based on our results, calibration of the positions of the Raman features and the twist angle in the structures with known θ would allow to identify the orientations of the component crystals in other samples, enabling a non-invasive method to determine the twist angle, even in structures encapsulated with other materials, where the graphene/graphene moiré pattern is not directly accessible for tunnelling spectroscopy studies [1, 2, 5, 6, 9–14].

ACKNOWLEDGEMENTS

This work has been supported by the UK Engineering and Physical Sciences Research Council (EPSRC) through the Centre for Doctoral Training in Condensed Matter Physics (CDT-CMP), Grant No. EP/L015544/1, as well as the University of Bath DTA Account, EPSRC Grant EP/M507982/1 and EPSRC Grants EP/S019367/1, EP/P026850/1 and EP/N010345/1, the European Graphene Flagship project (contract CNECTICT-604391), European Research Council Synergy Grant Hetero2D, the Royal Society and Lloyd’s Register Foundation Nanotechnology Programme. M. M.-K. also acknowledges funding through the University of Bath International Research Funding Scheme.

* Electronic address: m.mucha-kruczynski@bath.ac.uk

[1] Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, Unconventional superconductivity in magic-angle graphene superlattices, Nature 556, 43 (2018).

[2] Y. Cao, V. Fatemi, A. Demir, S. Fang, S. L. Tomarken, J. Y. Luo, J. D. Sanchez-Yamagishi, K. Watanabe, T. Taniguchi, E. Kaxiras, R. C. Ashoori, and P. Jarillo-Herrero, Correlated insulator behaviour at half-filling in magic-angle graphene superlattices, Nature 556, 80 (2018).

[3] Y. Xie, B. Lian, B. Jack, X. Liu, C.-L. Chiu, K. Watanabe, T. Taniguchi, B. A. Bernevig, and A. Yazdani, Spectroscopic signatures of many-body correlations in magic-angle twisted bilayer graphene, Nature 572, 101 (2019).

[4] Y. Choi, J. Kemmer, Y. Peng, A. Thomson, H. Arora, R. Polski, Y. Zhang, H. Ren, J. Alicea, G. Refael, F. von Oppen, K. Watanabe, T. Taniguchi, and S. Nadji-Perge, Electronic correlations in twisted bilayer graphene near the magic angle, Nature Physics 15, 1174 (2019).

[5] E. Codecido, Q. Wang, R. Koester, S. Che, H. Tian, R. Lv, S. Tran, K. Watanabe, T. Taniguchi, F. Zhang, M. Bockrath, and C. N. Lau, Correlated insulating and superconducting states in twisted bilayer graphene below the magic angle, Science Advances 5, eaaw9770 (2019).

[6] S. L. Tomarken, Y. Cao, A. Demir, K. Watanabe, T. Taniguchi, P. Jarillo-Herrero, and R. C. Ashoori, Electronic Compressibility of Magic-Angle Graphene Superlattices, Physical Review Letters 123, 046601 (2019).

[7] Y. Jiang, X. Lai, K. Watanabe, T. Taniguchi, K. Haule, J. Mao, and E. Y. Andrei, Charge order and broken rotational symmetry in magic-angle twisted bilayer graphene, Nature 573, 91 (2019).

[8] A. Kerelsky, L. J. McGilly, D. M. Kennes, L. Xian, M. Yankowitz, S. Chen, K. Watanabe, T. Taniguchi, J. Hone, C. Dean, A. Rubio, and A. N. Pasupathy, Maximised electron interactions at the magic angle in twisted bilayer graphene, Nature 572, 95 (2019).

[9] X. Lu, P. Stepanov, W. Yang, M. Xie, M. A. Aamir, I. Das, C. Urgell, K. Watanabe, T. Taniguchi, G. Zhang, A. Bachtold, A. H. MacDonald, and D. K. Efetov, Superconductors, orbital magnets and correlated states in magic-angle bilayer graphene, Nature 574, 653 (2019).

[10] M. Yankowitz, S. Chen, H. Polshyn, Y. Zhang, K. Watanabe, T. Taniguchi, D. Graf, A. F. Young, and C. R. Dean, Tuning superconductivity in twisted bilayer graphene, Science 363, 1059 (2019).

[11] P. Stepanov, I. Das, X. Lu, A. Fahimniya, K. Watanabe, T. Taniguchi, F. H. L. Koppens, J. Lischnier, L. Levitov, and D. K. Efetov, The interplay of insulating and superconducting orders in magic-angle graphene bilayers, arXiv:1911.09198 (2019).

[12] S. Chen, M. He, Y.-H. Zhang, V. Hsieh, Z. Fei, K. Watanabe, T. Taniguchi, D. H. Cobden, X. Xu, C. R. Dean, and M. Yankowitz, Electrically tunable correlated and topological states in twisted monolayer-bilayer graphene, arXiv:2004.11340 (2020).

[13] Y. Shi, S. Xu, M. M. Al Ezzi, N. Balakrishnan, A. Garcia-Ruiz, B. Tsim, C. Mullan, J. Barrier, N. Xin, B. A. Piot, T. Taniguchi, K. Watanabe, A. Carvalho, A. Mishchenko, A. K. Geim, V. I. Falko, S. Adam, A. H. Castro Neto, and K. S. Novoselov, Tunable van Hove Singularities and Correlated States in Twisted Trilayer Graphene, arXiv:2004.12414 (2020).

[14] K.-T. Tsai, X. Zhang, Z. Zhu, Y. Luo, S. Carr, M. Luskin, E. Kaxiras, and K. Wang, Correlated Superconducting and Insulating States in Twisted Trilayer Graphene Moiré of Moiré Superlattices, arXiv:1912.03375 (2019).

[15] X. Li, P. Wu, and A. H. MacDonald, Electronic Structure of Single-Twist Trilayer Graphene, arXiv:1907.12338 (2019).

[16] Z. Ma, S. Li, Y.-W. Zheng, M.-M. Xiao, H. Jiang, J.-H. Gao, and X. C. Xie, Topological flat bands in twisted trilayer graphene, arXiv:1905.00622 (2019).

[17] Y.-H. Zhang, D. Mao, Y. Cao, P. Jarillo-Herrero, and
T. Senthil, Nearly flat Chern bands in moiré superlattices, Physical Review B 99, 075127 (2019).

[18] C. Xu and L. Balents, Topological Superconductivity in Twisted Multilayer Graphene, Physical Review Letters 121, 087001 (2018).

[19] S. Carr, C. Li, Z. Zhu, E. Kaxiras, S. Sachdev, and A. Kruchkov, Coexistence of ultraheavy and ultra-relativistic Dirac quasiparticles in sandwiched trilayer graphene, arXiv:1907.00952 (2019).

[20] E. Khalaf, A. J. Kruchkov, G. Tarnopolsky, and A. Vishwanath, Magic angle hierarchy in twisted graphene multilayers, Physical Review B 100, 085109 (2019).

[21] C. Mora, N. Regnault, and B. A. Bernevig, Flatbands and Perfect Metal in Trilayer Moiré Graphene, Physical Review Letters 123, 026402 (2019).

[22] A. C. Ferrari and D. M. Basko, Raman spectroscopy as a versatile tool for studying the properties of graphene, Nature Nanotechnology 8, 235 (2013).

[23] Z. Ni, L. Liu, Y. Wang, Z. Zheng, L.-J. Li, T. Yu, and Z. Shen, G-band Raman double resonance in twisted bilayer graphene: Evidence of band splitting and folding, Physical Review B 80, 125404 (2009).

[24] R. W. Havener, H. Zhuang, L. Brown, R. G. Hennig, and J. Park, Angle-Resolved Raman Imaging of Interlayer Rotations and Interactions in Twisted Bilayer Graphene, Nano Letters 12, 3162 (2012).

[25] K. Kim, S. Coh, L. Z. Tan, W. Regan, J. M. Yuk, E. Chatterjee, M. F. Crommie, M. L. Cohen, S. G. Louie, and A. Zettl, Raman Spectroscopy Study of Rotated Double-Layer Graphene: Misorientation-Angle Dependence of Electronic Structure, Physical Review Letters 108, 246103 (2012).

[26] Y. Wang, Z. Su, W. Wu, S. Nie, N. Xie, H. Gong, Y. Guo, J. H. Lee, S. Xing, X. Lu, H. Wang, X. Lu, K. McCarty, S. Pei, F. Robles-Hernandez, V. G. Hadjiev, and J. Bao, Resonance Raman spectroscopy of G-line and folded phonons in twisted bilayer graphene with large rotation angles, Applied Physics Letters 103, 123101 (2013).

[27] V. Carozo, C. M. Almeida, E. H. M. Ferreira, L. G. Cancado, C. A. Achete, and A. Jorio, Raman Signature of Graphene Superlattices, Nano Letters 11, 4527 (2011).

[28] J. Campos-Delgado, L. G. Cancado, C. A. Achete, A. Jorio, and J.-P. Raskin, Raman scattering study of the phonon dispersion in twisted bilayer graphene, Nano Research 6, 269 (2013).

[29] R. He, T.-F. Chung, C. Delaney, C. Keiser, L. A. Jau-regui, P. M. Shand, C. C. Chancey, Y. Wang, J. Bao, and Y. P. Chen, Observation of Low Energy Raman Modes in Twisted Bilayer Graphene, Nano Letters 12, 3162 (2012).

[30] J.-B. Wu, X. Zhang, M. Ijas, W.-P. Han, X.-F. Qiao, X.-L. Li, D.-S. Jiang, A. C. Ferrari, and P.-H. Tan, Resonant Raman spectroscopy of twisted multilayer graphene, Nature Communications 5, 5309 (2014).

[31] O. Kashuba and V. I. Fal’ko, Signature of electronic excitations in the Raman spectrum of graphene, Physical Review B 80, 241404 (2009).

[32] M. Mucha-Kruzcynski, O. Kashuba, and V. I. Fal’ko, Spectral features due to inter-Landau-level transitions in the Raman spectrum of bilayer graphene, Physical Review B 82, 045405 (2010).

[33] E. Riccardi, M.-A. Measson, M. Cazayous, A. Sacuto, and Y. Gallais, Gate-Dependent Electronic Raman Scattering in Graphene, Physical Review Letters 116, 066805 (2016).

[34] E. Riccardi, O. Kashuba, M. Cazayous, M.-A. Measson, A. Sacuto, and Y. Gallais, Probing chiral electronic excitations in bilayer graphene by Raman scattering, Physical Review Materials 3, 014002 (2019).

[35] C. Faugeras, M. Amado, P. Kossacki, M. Orlita, M. Kuhne, A. A. L. Nicolet, Yu. I. Latyshev, and M. Potemski, Magneto-Raman Scattering of Graphene on Graphite: Electronic and Phonon Excitations, Physical Review Letters 107, 036807 (2011).

[36] Y. Henni, H. P. O. Collado, K. Nogajewski, M. R. M. Molas, G. Usaj, C. A. Balseiro, M. Orlita, M. Potemski, and C. Faugeras, Rhombohedral Multilayer Graphene: A Magneto-Raman Scattering Study, Nano Letters 16, 3710 (2016).

[37] A. García-Ruiz, S. Slizovskiy, M. Mucha-Kruzcynski, and V. I. Fal’ko, Spectroscopic Signatures of Electronic Excitations in Raman Scattering in Thin Films of Rhombohedral Graphite, Nano Letters 19, 6152 (2019).

[38] A. García-Ruiz, M. Mucha-Kruzcynski, and V. I. Fal’ko, Superconductivity-induced features in the electronic Raman spectrum of monolayer graphene, Physical Review B 97, 155405 (2018).

[39] Yu. S. Ponomov, A. V. Ushakov, and S. V. Streletsov, Electronic Raman scattering in graphite and single-layer and few-layer graphene, Physical Review B 91, 195435 (2015).

[40] M. Kuhne, C. Faugeras, P. Kossacki, A. A. L. Nicolet, M. Orlita, Yu. I. Latyshev, and M. Potemski, Polarization-resolved magneto-Raman scattering of graphene-like domains on natural graphite, Physical Review B 85, 195406 (2012).

[41] C. Faugeras, P. Kossacki, A. A. L. Nicolet, M. Orlita, M. Potemski, A. Mahmood, and D. M. Basko, Probing the band structure of quadrilayer graphene with magneto-phonon resonance, New Journal of Physics 14, 095007 (2012).

[42] S. Berciaud, M. Potemski, and C. Faugeras, Probing Electronic Excitations in Mono- to Pentalayer Graphene by Micro Magneto-Raman Spectroscopy, Nano Letters 14, 4548 (2014).

[43] T. Stauber, P. San-Jose, and L. Brey, Optical conductivity, Drude weight and plasmons in twisted graphene bilayers, New Journal of Physics 15, 113050 (2013).

[44] P. Moon and M. Koshino, Optical absorption in twisted bilayer graphene, Physical Review B 87, 205404 (2013).

[45] G. Li, A. Luican, J. M. B. Lopes dos Santos, A. H. Castro Neto, A. Reina, J. Kong, and E. Y. Andrei, Observation of Van Hove singularities in twisted graphene layers, Nature Physics 6, 109, (2010).

[46] J. M. Dos Santos, R. M. Peres, and A. H. Castro Neto, Graphene Bilayer with a Twist: Electronic Structure, Physical Review Letters 99, 256802 (2007).

[47] R. Bistritzer and A. H. MacDonald, Moiré bands in twisted double-layer graphene, Proceedings of National Academy of Sciences 108, 12233 (2011).

[48] E. McCann and M. Koshino, Reports on Progress in Physics 76, 056503 (2013).

[49] H. Yoo, R. Engelke, S. Carr, S. Fang, K. Zhang, P. Cazeaux, S. H. Sung, R. Hovden, A. W. Tseng, T. Taniguchi, K. Watanabe, G.-C. Yi, M. Kim, M. Luskin, E. B. Tadmor, E. Kaxiras, and P. Kim, Atomic and electronic reconstruction at the van der Waals interface in twisted bilayer graphene, Nature Materials 15, 130 (2016).
[50] M. Koshino and E. McCann, Parity and valley degeneracy in multilayer graphene, Physical Review B 81, 115315 (2010).

[51] M. Koshino and E. McCann, Trigonal warping and Berry’s phase $N\pi$ in ABC-stacked multilayer graphene, Physical Review B 80, 165409 (2009).