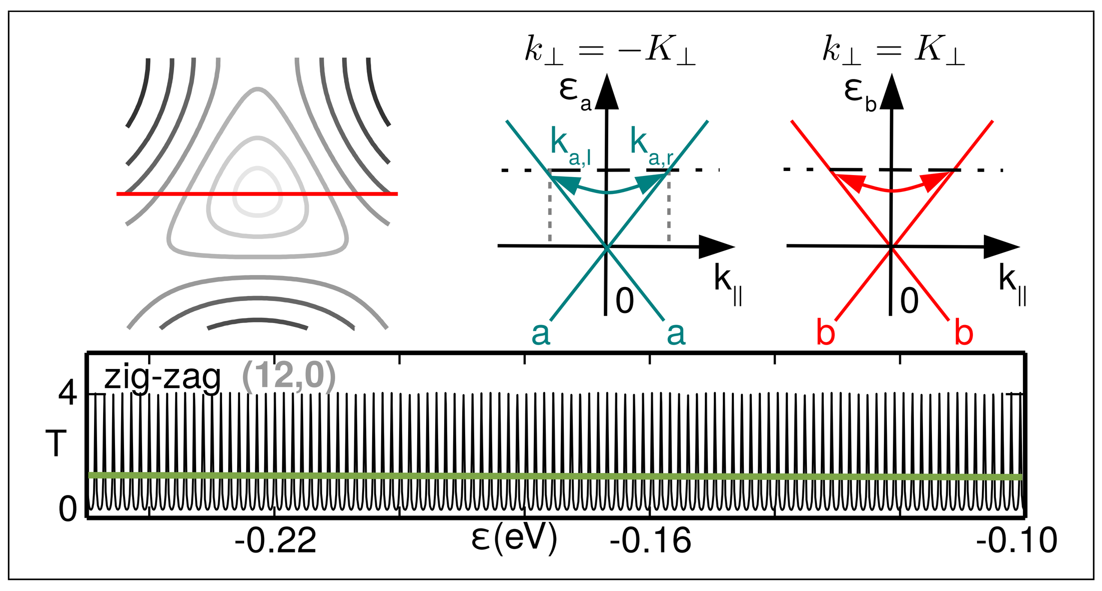
Secondary electron interference from trigonal warping in clean carbon nanotubes [1]

A. Dirnaichner, M. del Valle, K. J. G. Götz, F. J. Schupp,
N. Paradiso, M. Grifoni, A. K. Hüttel, and Ch. Strunk

University of Regensburg, 93040 Regensburg, Germany

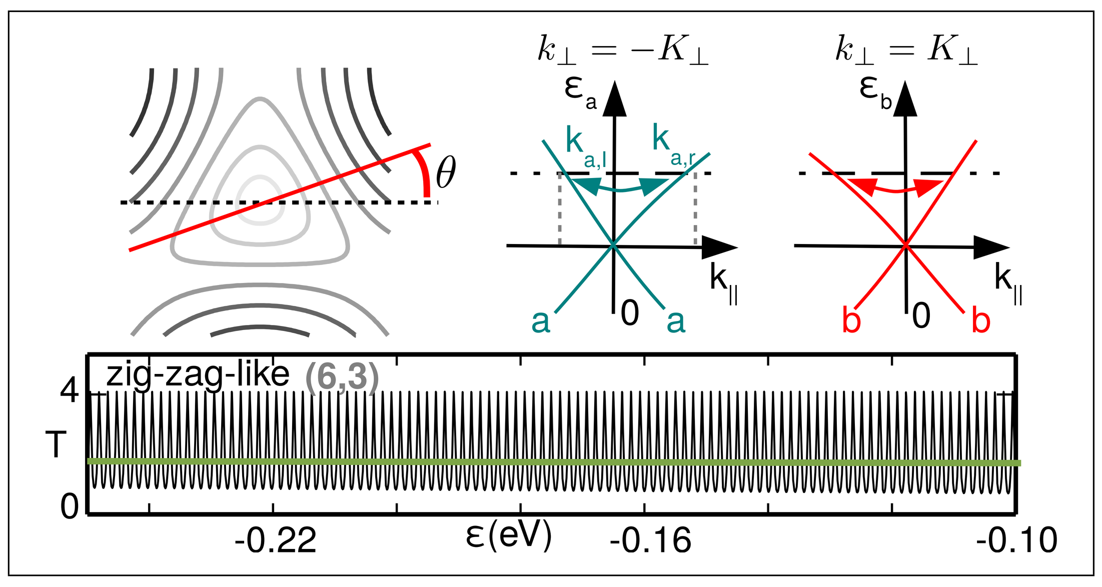
Interference and CNT symmetry

- real-space tight-binding calculations [2]
- four nanotube symmetry classes [3, 4, 5]



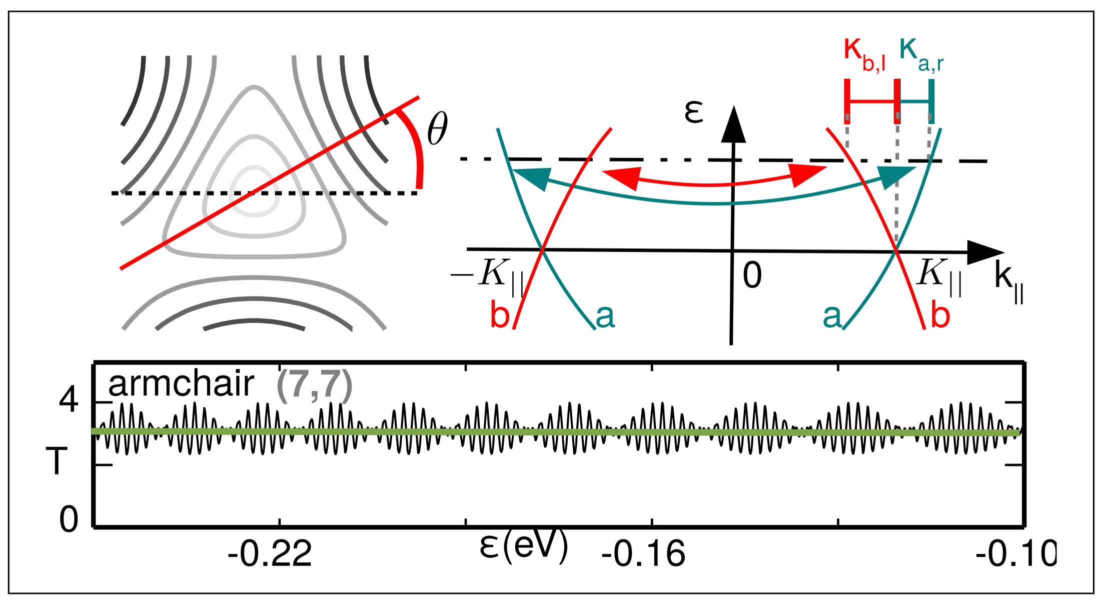
zigzag ($\theta = 0°$, (n,0)):

- Dirac cones around $k_\perp = \pm K_\perp$
- only backscattering within cone, J-conservation
- two channels, identical accumulated phase



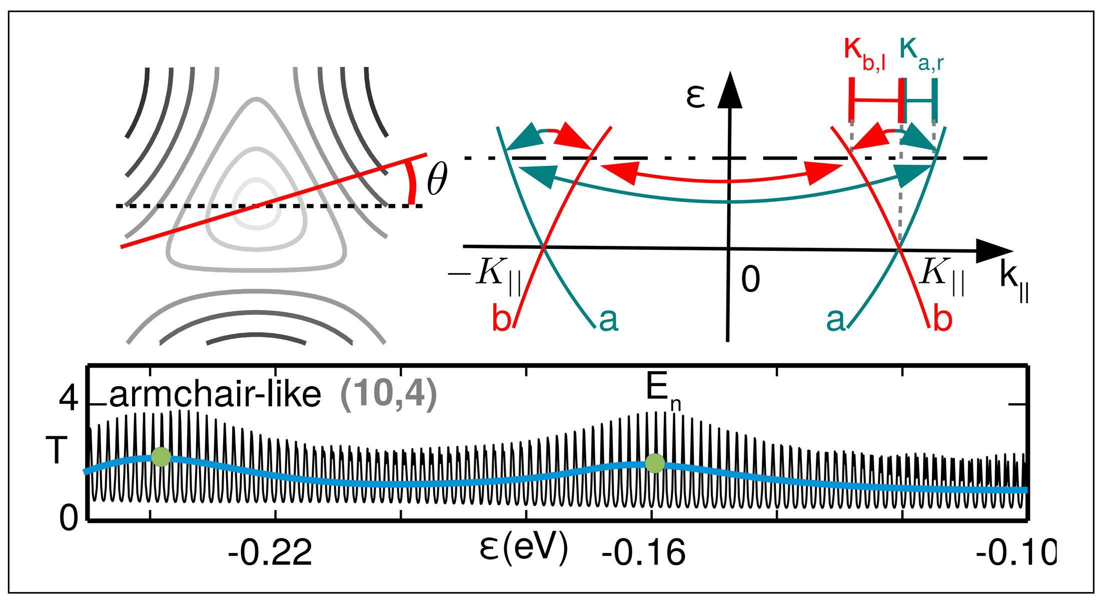
zigzag-like ($0° < \theta < 30°$, $\frac{n-m}{3\,\mathrm{gcd}(n,m)} \notin \mathbb{Z}$):

- asymmetric Dirac cones around $k_\perp = \pm K_\perp$
- only backscattering within cone, J-conservation
- two channels, identical accumulated phase



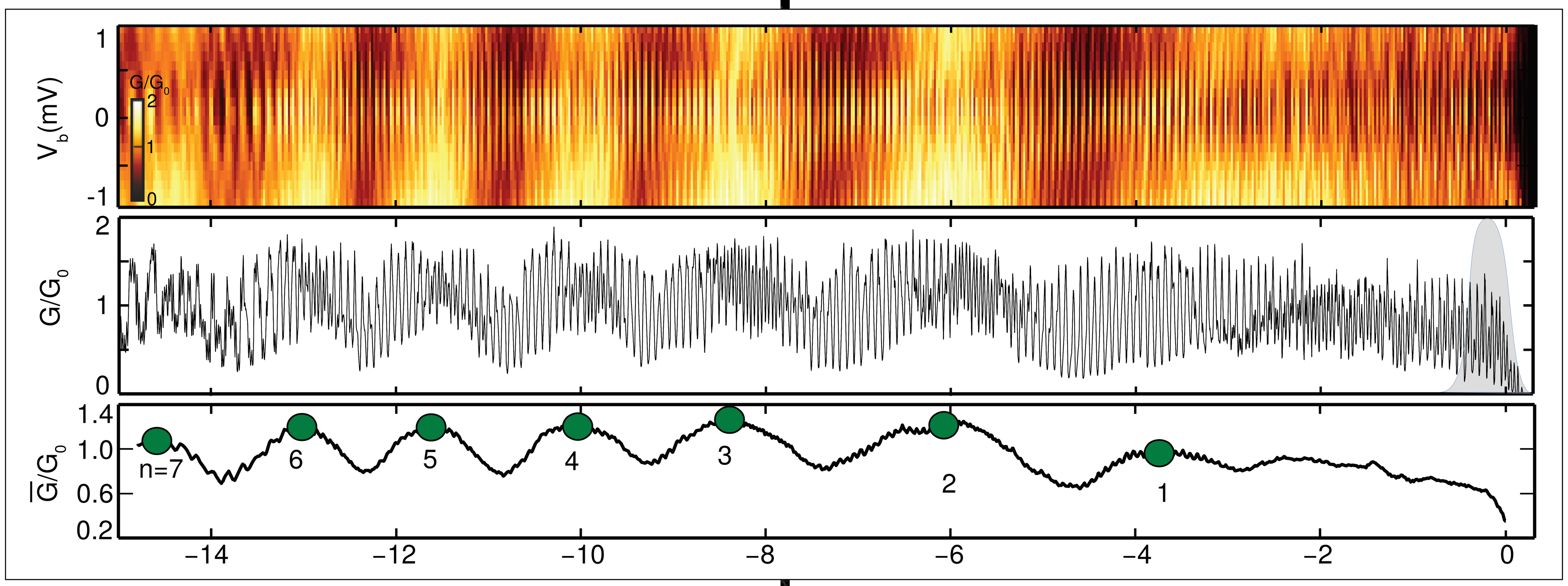
armchair ($\theta = 30°$, (n,n)):

- Dirac cones at $k_\perp = 0$; parity symmetry
- only backscattering within a/b branch
- two channels, different accumulated phase, beat

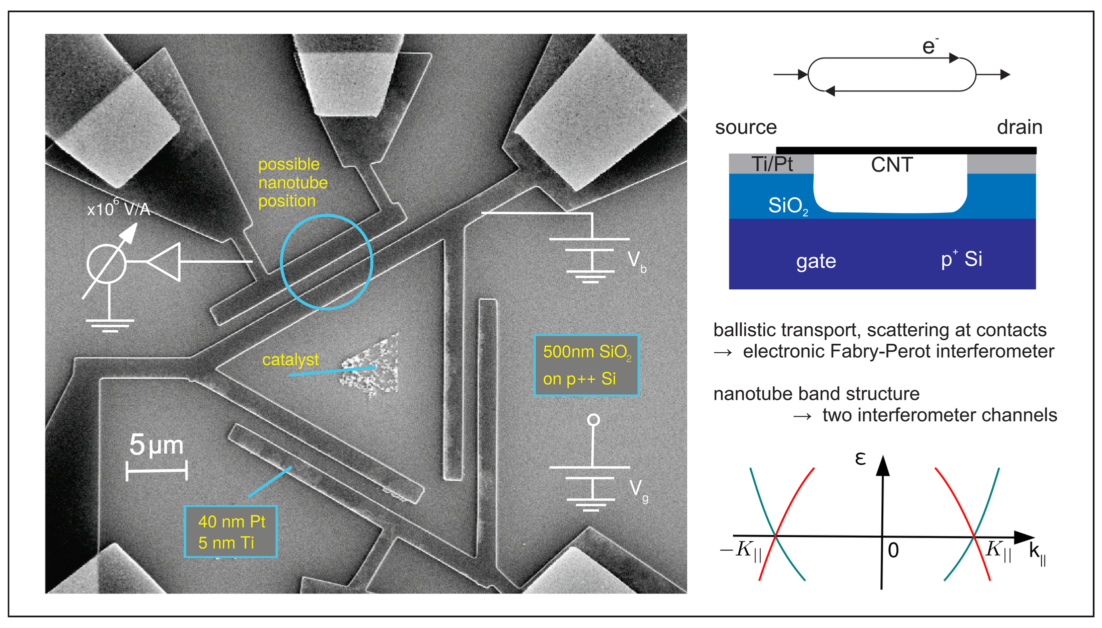


armchair-like ($0° < \theta < 30°$, $\frac{n-m}{3\,\mathrm{gcd}(n,m)} \in \mathbb{Z}$):

- Dirac cones at $k_\perp = 0$; NO parity symmetry
- mixing of channels with different phase
- beat plus slow modulation of $\bar{G}$

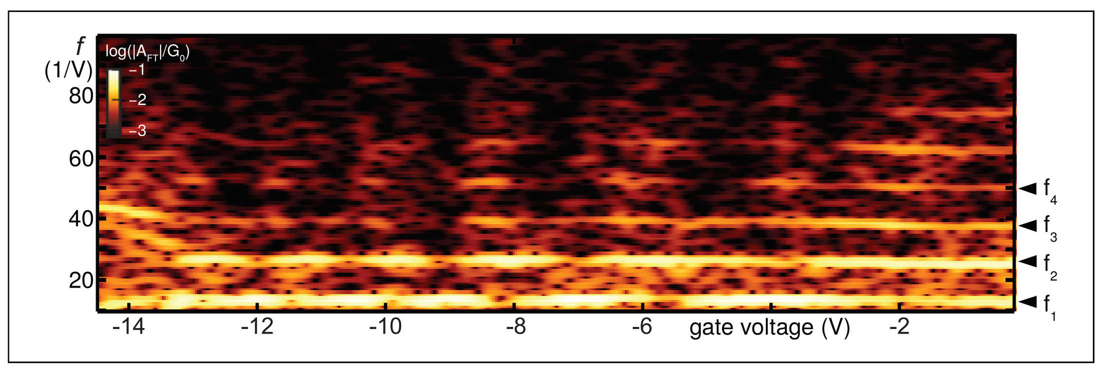


Carbon nanotube interferometer



- Pt/Ti leads, 1.2 µm wide trench
- clean "overgrowth" CNT fabrication [6, 7, 8]
- transport measurements at $T = 15\,$mK
- ballistic transport, only scattering at contacts
- two-channel Fabry-Perot interferometer [9]

Interference pattern

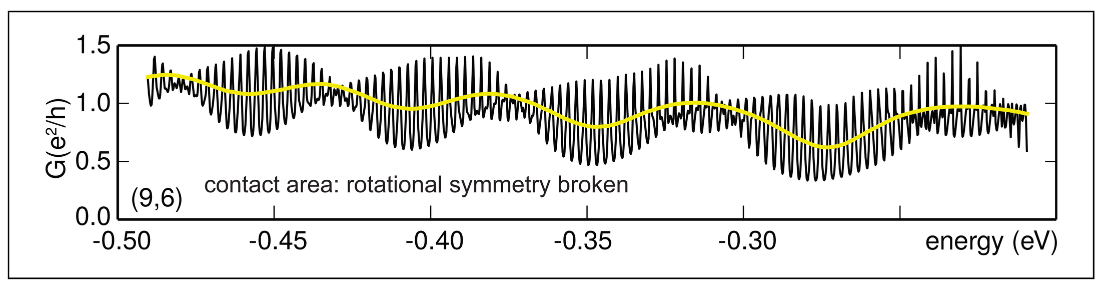


- fundamental frequency ↔ device length

$$L_{\mathrm{FP}} = \frac{f_1 \pi \hbar v_F}{\alpha e} \simeq 1\,\mu\mathrm{m} \quad \leftrightarrow \quad L_{\mathrm{trench}} = 1.2\,\mu\mathrm{m}$$

- only multiples of one fundamental frequency in the data ⟶ no additional scatterers
- frequency doubling / beat — two channels
- slow modulation of $\bar{G}$ — channel mixing
- either armchair-like, or symmetry broken

Rotational symmetry breaking



- contact areas: bottom of CNT touches metal
- model in tight-binding calculation: differing on-site energies in upper / lower half of CNT
- zigzag-like — scattering between different J ⟶ channel mixing, slow modulation of $\bar{G}$ restored

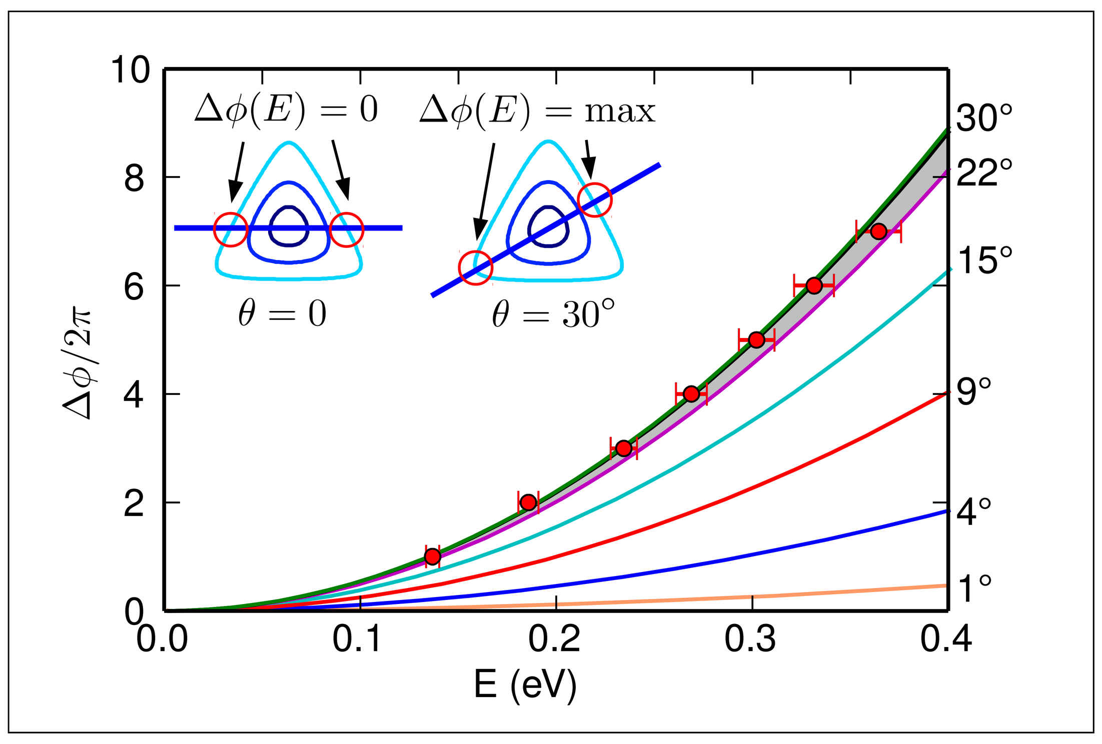
Chiral angle determination

- slow modulation in an armchair-like CNT with chiral angle θ: phase difference of modes

$$\Delta\phi^\theta(E) = |\phi_a^\theta(E) - \phi_b^\theta(E)| = \\ = 2|k^\theta_{a,r} - k^\theta_{b,l}|L = 2|\kappa^\theta_{a,r} - \kappa^\theta_{b,l}|L$$

$\kappa^\theta_{i,j}$: longit. wave vectors measured from K/K'

- conductance peak when $\Delta\phi^\theta(E) = 2\pi n$



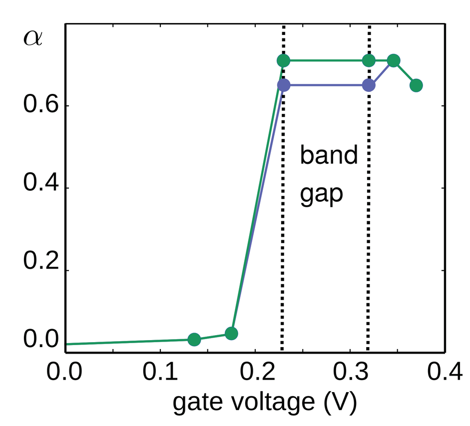
- calculate $\Delta\phi^\theta(E)$, compare with data
- result for device: $22° \leq \theta < 30°$

Error sources

- band gap at $V_g > 0$, energy offset
- lever arm $\alpha(V_g)$ hard to determine, varies strongly

→ $55\,\mathrm{meV} < \Delta E < 60\,\mathrm{meV}$

→ error bars in figure



- value tight-binding overlap integral? [10, 11, 12]
- $2.5\,\mathrm{eV} \lesssim t \lesssim 2.6\,\mathrm{eV}$ consistent with our data

References

[1] A. Dirnaichner *et al.*, arXiv:1602.03866 (2016).
[2] M. del Valle *et al.*, PRB **84**, 165427 (2011).
[3] A. M. Lunde *et al.*, PRB **71**, 125408 (2005).
[4] M. Marganska *et al.*, PRB **92**, 075433 (2015).
[5] E. A. Laird *et al.*, RMP **87**, 703 (2015).
[6] J. Cao *et al.*, Nature Materials **4**, 745 (2005).
[7] G. A. Steele *et al.*, Nature Nanotechn. **4**, 363 (2009).
[8] A. K. Hüttel *et al.*, Nano Letters **9**, 2547 (2009).
[9] W. Liang *et al.*, Nature **411**, 665 (2001).
[10] R. Saito, M. Dresselhaus, and G. Dresselhaus, *Physical Properties Of Carbon Nanotubes* (World Scientific, 1998).
[11] M. Ouyang *et al.*, Science **292**, 702 (2001).
[12] J. W. G. Wildoer *et al.*, Nature **391**, 59 (1998).

We gratefully acknowlegde funding by the DFG via the Emmy Noether grant Hu1808/1, SFB 689, and GRK1570 "Electronic Properties of Carbon Based Nanostructures".