Mode Mixing in Graphene p-n Junctions Investigated by Shot Noise Measurement

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Outline

Introduction

- Graphene *p-n* junction (PNJ)
- Bipolar quantum Hall states
- Expected shot noise at a PNJ

Device structure

- Graphene bipolar device for shot noise measurements

Results and discussions

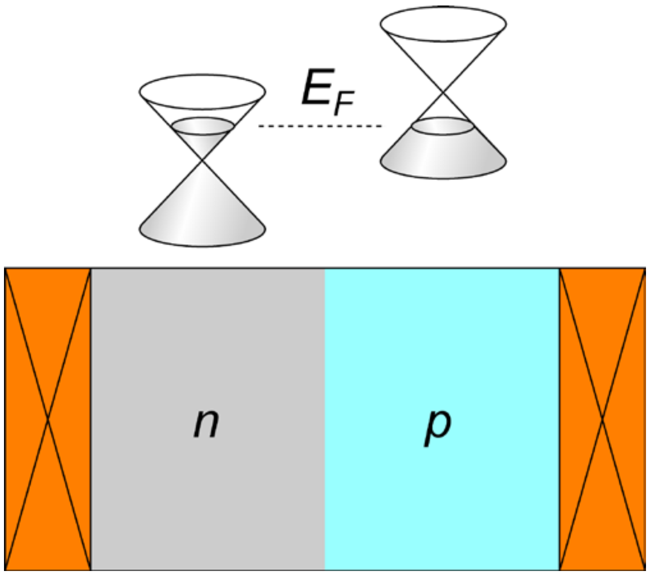
- Energy relaxation along PNJs
- Beam splitter properties of PNJs

Introduction: graphene *p-n* junction

Graphene Linear and gapless band structure

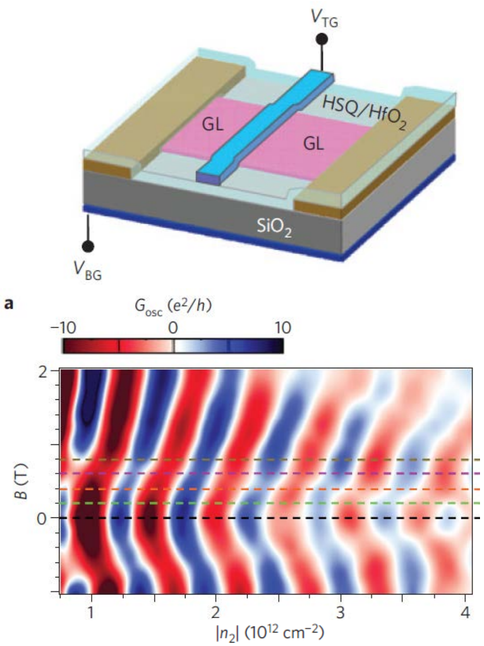
- massless Dirac Fermion
- symmetric electron and hole properties
- adjacent electron and hole regions

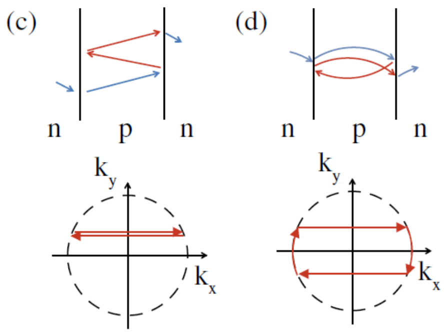
→ Unique system to investigate transport of Dirac Fermions across PNJs



Introduction: graphene *p-n* junction

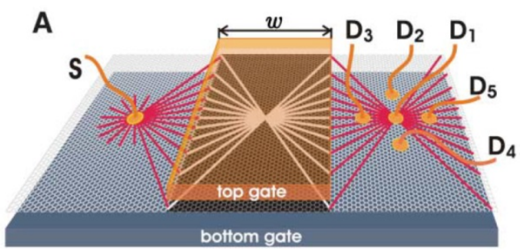
Klein tunneling





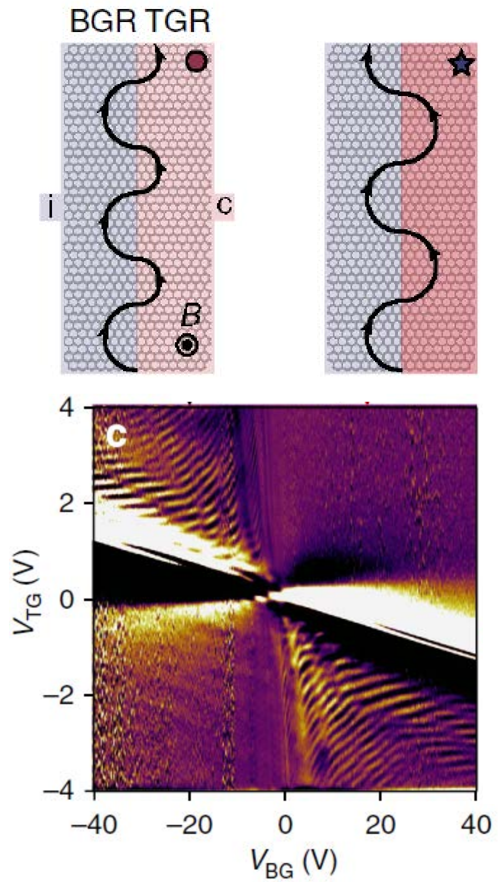
Nature Phys. **5**, 222 (2009)
Nat. Commun. **4**, 2342 (2013).
Jpn. J. Appl. Phys. **52**, 110105 (2013).

Veselago lensing



Theory:
Science 315, 1253 (2007).

Snake state



Theory:
Phys. Rev. B **81**, 241406 (2010).

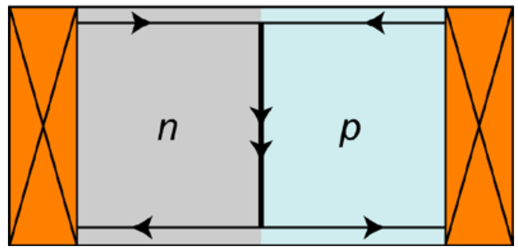
Experiment:
Phys. Rev. Lett. **107**,046602 (2011).
Nat. Commun. 6, 6470 (2015)
Nat. Commun. 6, 6093 (2015).

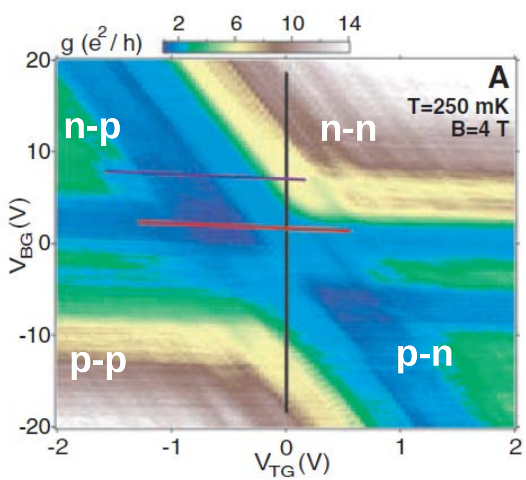
Introduction: graphene bipolar QH state

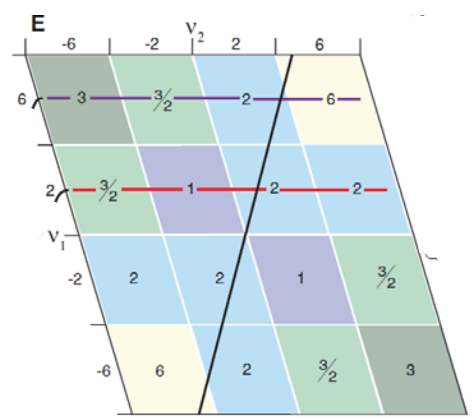
Combination of QH physics and characteristic transport at PNJ leads to quantized conductance at unusual values.

Bipolar QH state

$$G = \frac{|\nu||\nu'|}{|\nu|+|\nu'|} \times e^2/h$$







Experiment: Science **317**, 638 (2007)

Theory: Science **317**, 641 (2007)

Introduction: graphene bipolar QH state

Combination of QH physics and characteristic transport at PNJ leads to quantized conductance at unusual values.

Bipolar QH state

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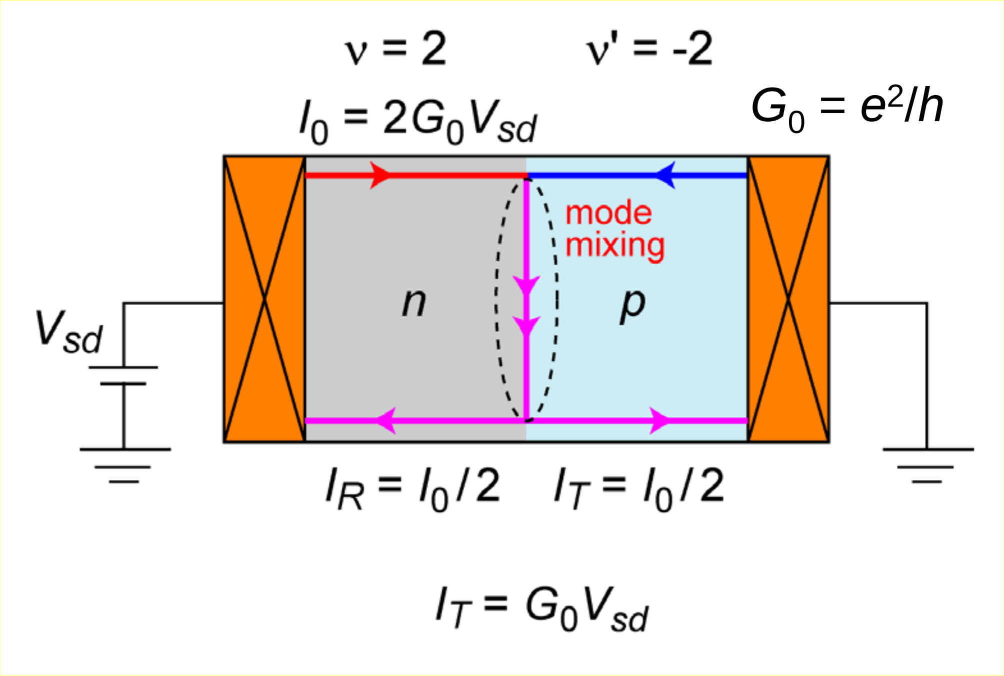
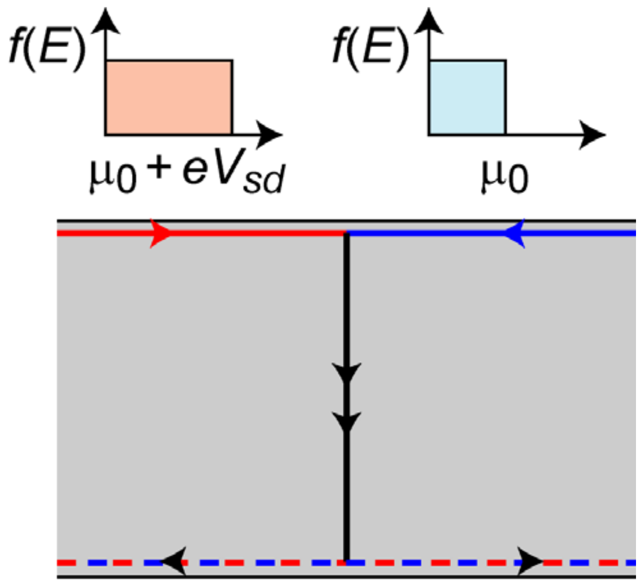


Experiment: Science **317**, 638 (2007)

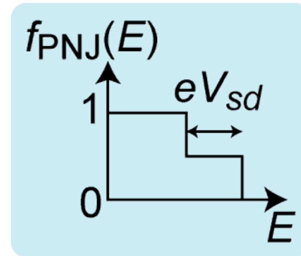
Theory: Science **317**, 641 (2007)

Introduction: shot noise at graphene *p-n* junction



shot noise

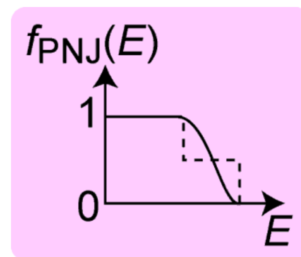
Shot noise depends on the energy distribution in the PNJ.



<u>quasi-elastic scattering</u>

double-step function:

$F = 0.25$

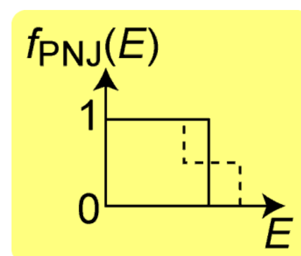


$T_{eff} = eV_{sd}$

<u>inelastic scattering in the PNJ</u>

hot Fermi function:

$F = 0.28$



<u>inelastic scattering with external states</u>

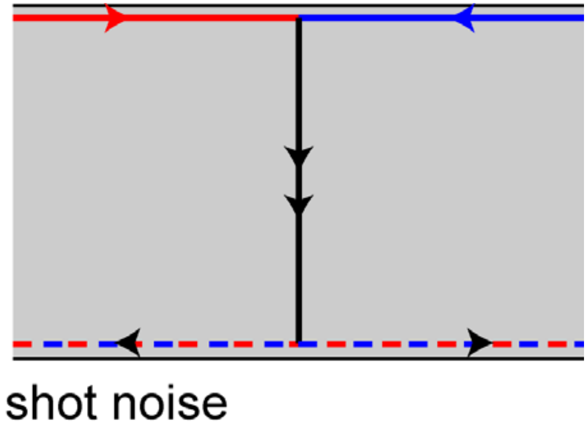
cold Fermi function:

$F = 0$

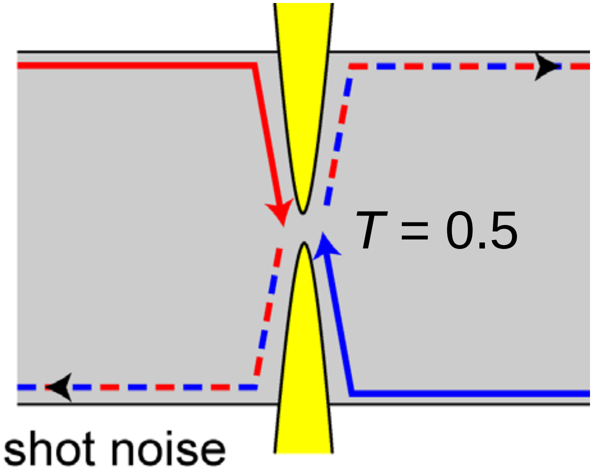
Note: transport measurement gives $G = e^2/h$ for all the cases.

Introduction: shot noise at graphene *p-n* junction

PNJ in graphene



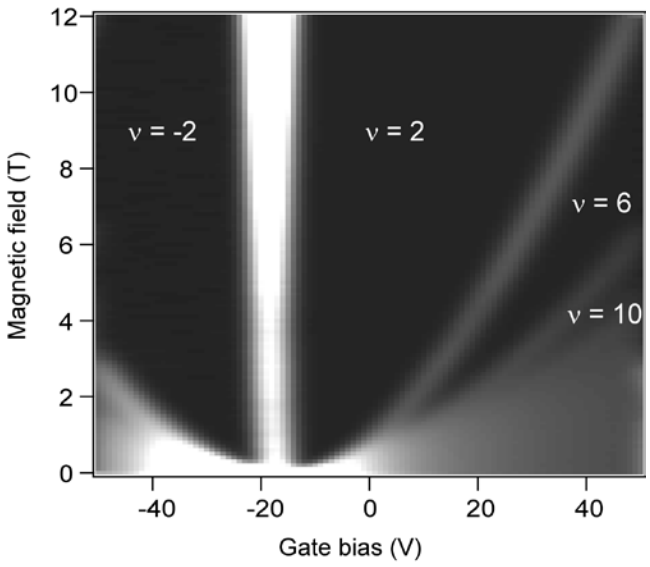
QPC in standard semiconductor



In the case of elastic mode mixing, a PNJ can serve as a beam splitter.

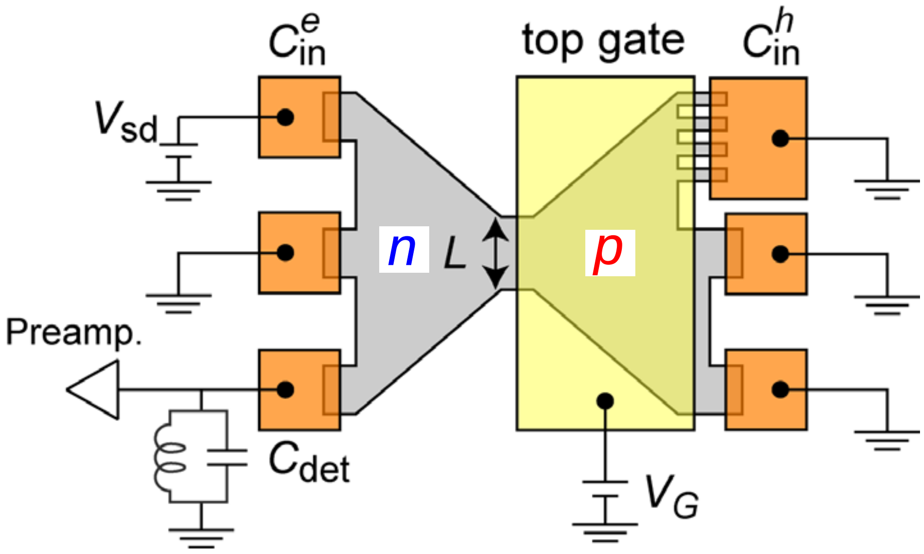
Experiment: device structure

R_{xx} in a Hall bar device



- graphene on SiC
- $n \sim 5 \times 10^{11}$ cm^{-2}

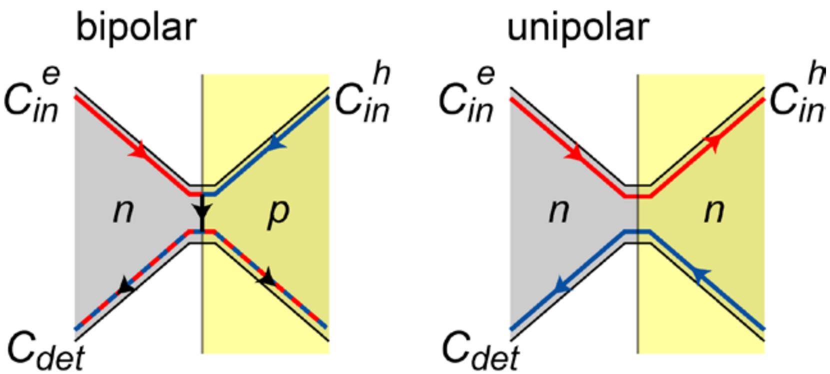
Device structure for noise measurement



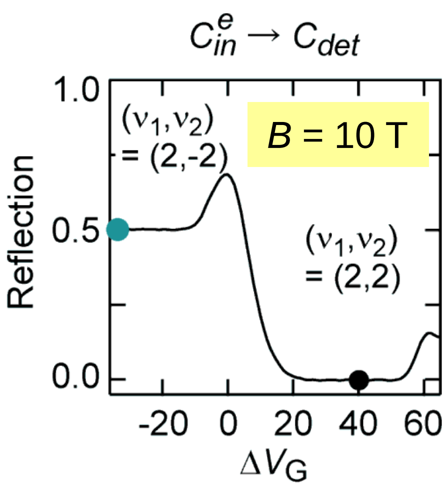
L = 5, 10, 20, 50, 100 μm

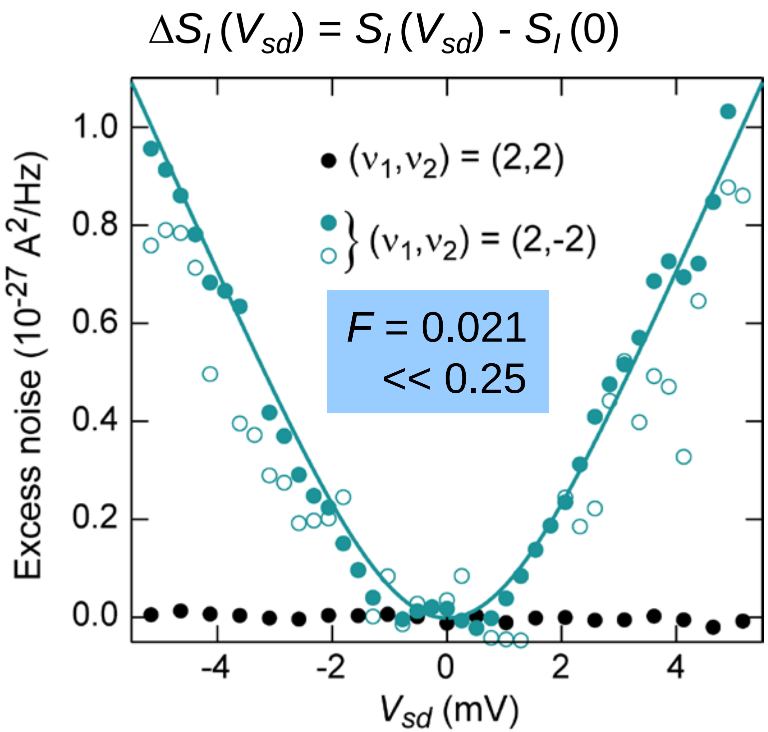
noise measurement at 3 MHz

Results: shot noise generated by *p-n* junction



L = 50 μm





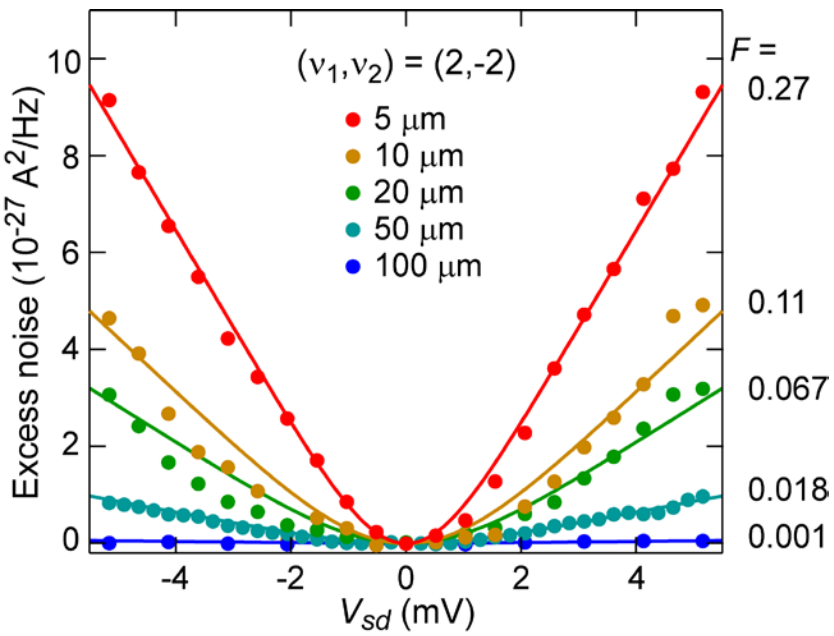
$$\Delta S_I = 2eFG_{\mathrm{PNJ}}V_{sd}\left[\coth\left(\frac{eV_{sd}}{2k_BT}\right) - \frac{2k_BT}{eV_{sd}}\right]$$

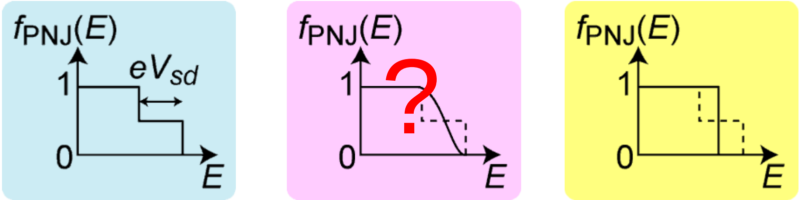
- Shot noise is generated by the PNJ.
- *F* is much smaller than that expected for double-step function.

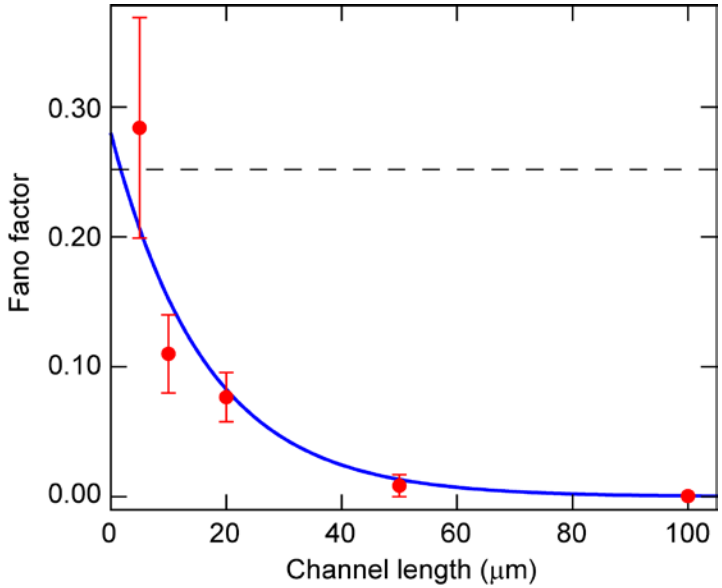
⇨ Energy distribution changes in the 50-μm-long PNJ.

Results: shot noise generated by *p-n* junction

Shot noise for several L







Shot noise decreases with increasing L.

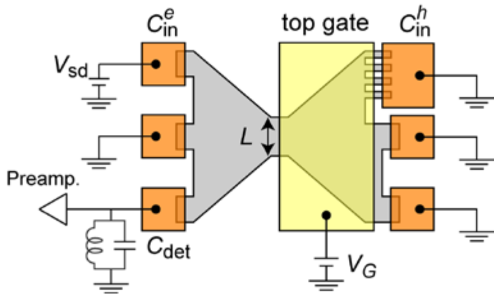
Energy relaxation

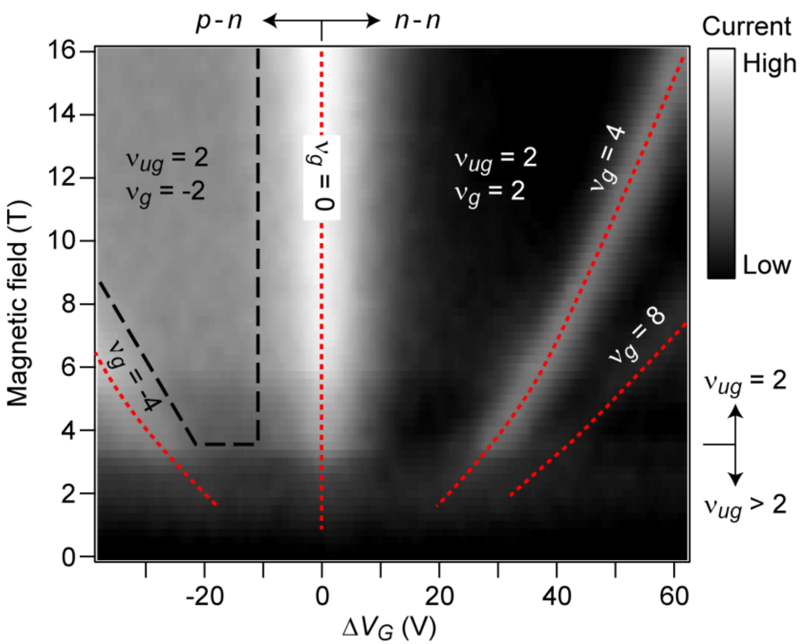
Relaxation length L_0 = 16 μm

The behavior can be explained by the coupling to cold external states.

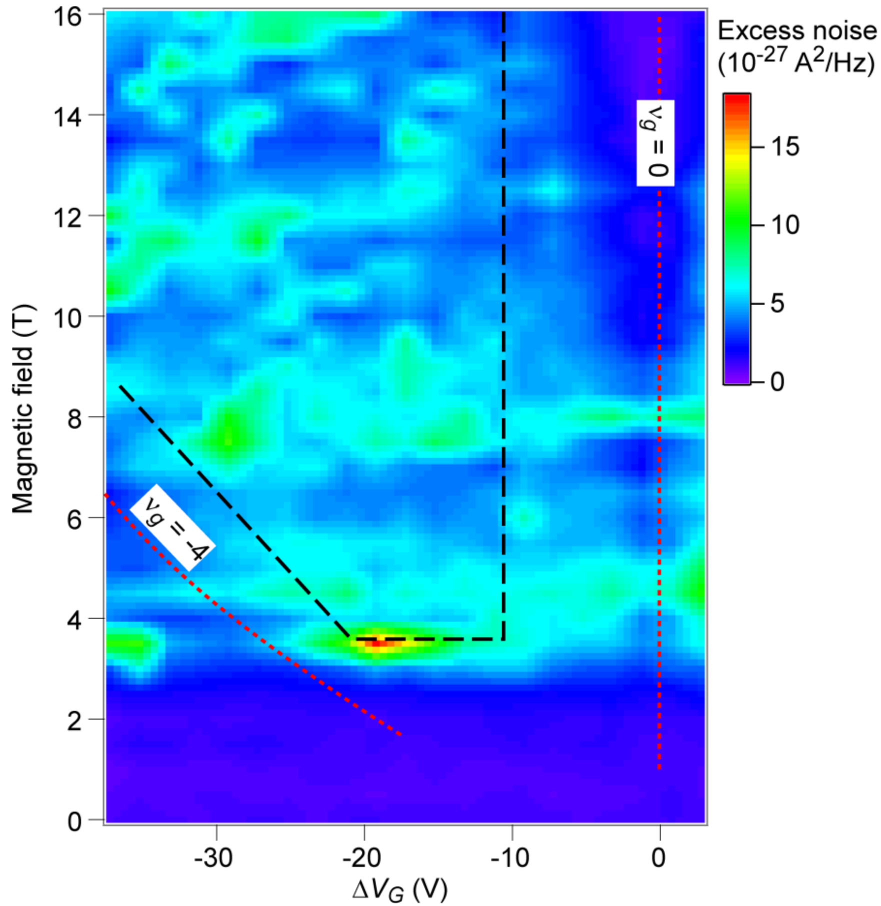
Energy loss is negligible when $L \ll L_0$ = 16 μm

Results: shot noise generated by *p-n* junction



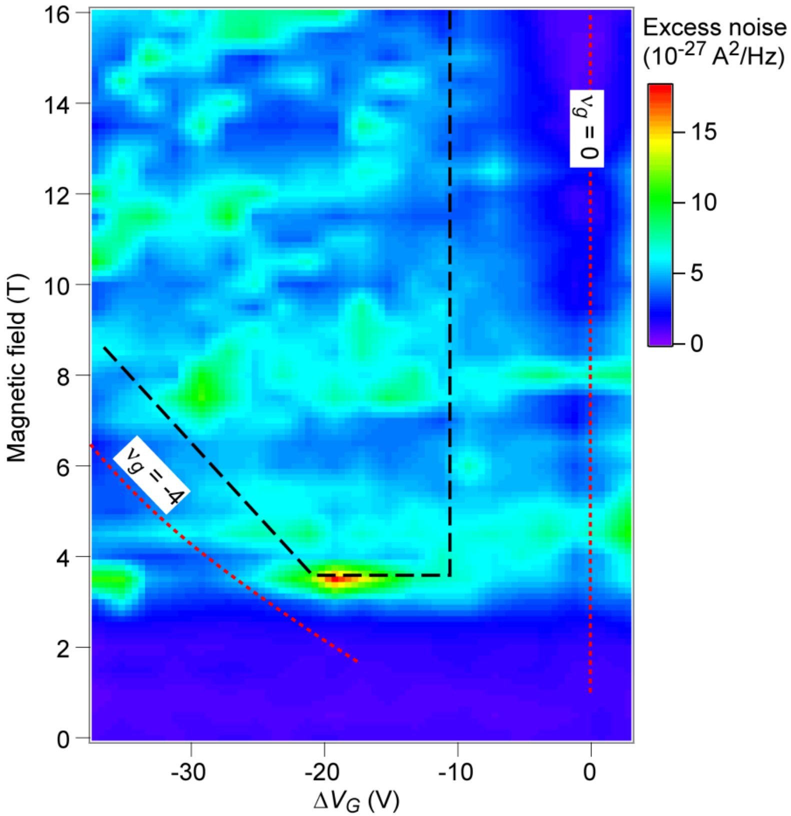


Current in the bipolar QH state is constant within 2%.



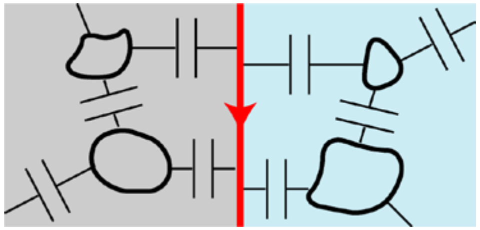
Noise in the bipolar QH state fluctuates by 50%.

Results: shot noise generated by *p-n* junction



Origin of the noise fluctuations

Fluctuations of the energy relaxation through interactions with localized states.



Energy level and profile of localized states depend on *B* and V_G.

Summary

Noise measurement in graphene bipolar QH state

Noise is generated by a p-n junction.

⇨ Mode mixing at a p-n junction leads to non-equilibrium energy distribution.

Fano factor decreases with increasing PNJ length (relaxation length 16 μm).

⇨ Energy distribution relaxes toward equilibrium Fermi distribution.

Beam splitter could be realized in graphene, encouraging electronic quantum optics experiments using graphene.