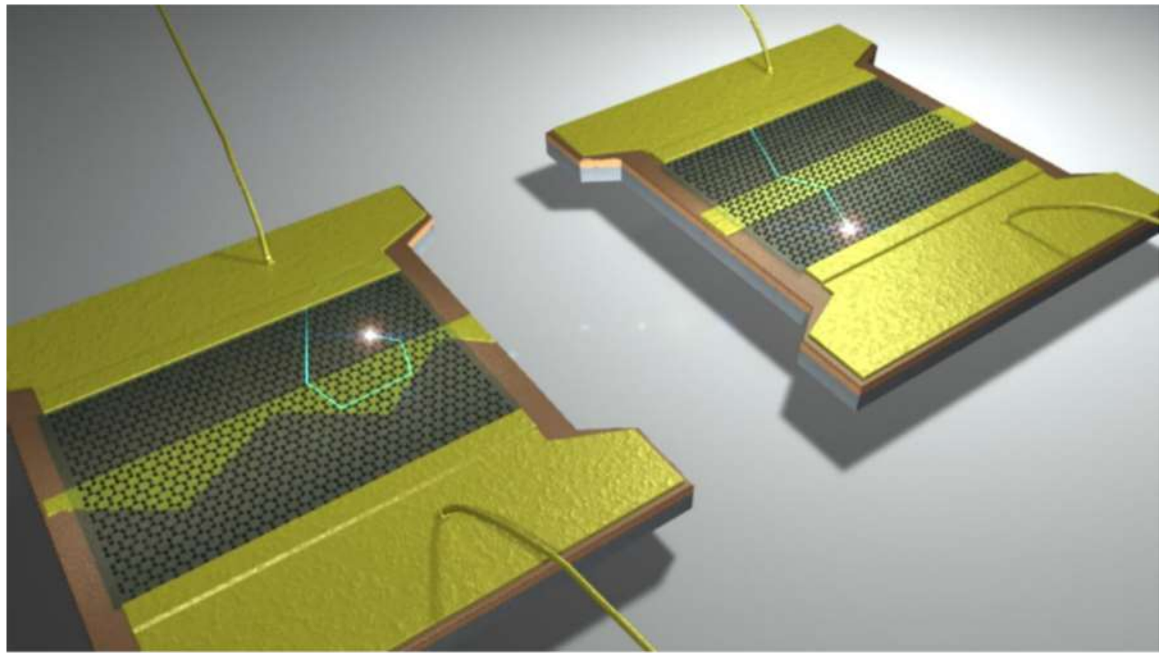
laboratoire pierre aigrain
électronique et photonique quantiques

GRAPHENE FLAGSHIP

# Probing electron optics in a Dirac fermion reflector




**H. Graef[1,2], M. Rosticher[1], D. Mele[1], Q. Wilmart[1] , L. Banszerus[3], C. Stampfer[3], T. Taniguchi[4], K. Watanabe[4], E. Bocquillon[1], G. Fève[1], J.M. Berroir[1], E.H.T. Teo[2] and B. Plaçais[1]**

[1]Laboratoire Pierre Aigrain – ENS, Paris, France; [2]CINTRA – Nanyang Technological University, Singapore; [3]2nd Institute of Physics A – RWTH Aachen, Germany; [4]National Institute for Materials Science, Tsukuba, Japan

# Outline

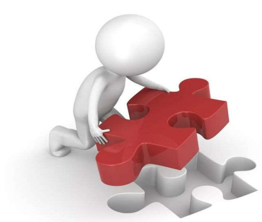
Dirac Fermion Optics (DFO)

Sample fabrication

Coherent electron optics in the DFR

Experimental demonstration of the DFR

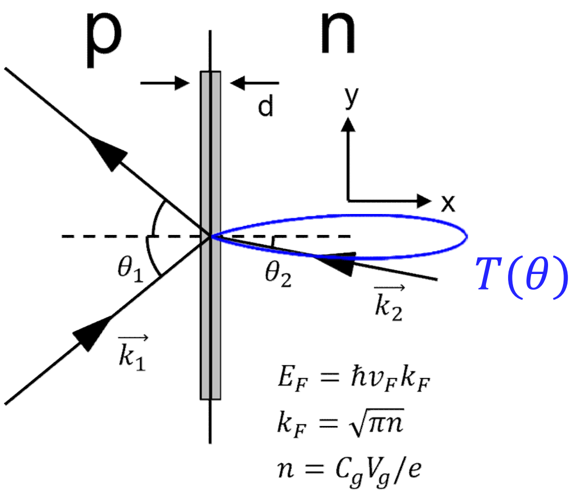
Effect of acoustic phonon scattering

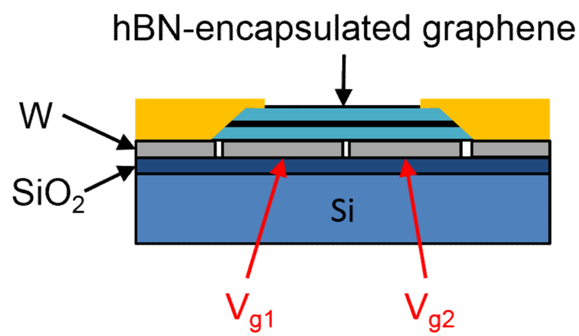


Conclusion

Electronic transport measurements

# Dirac Fermion Optics (DFO)



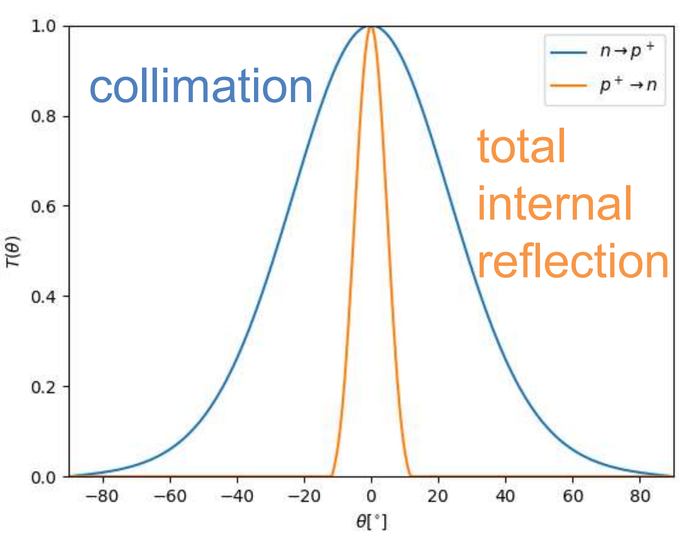




| | Photon optics (3D) | Dirac fermion optics (2D) |
|---|---|---|
| **Medium** | transparent | ballistic |
| **Phase velocity** | $3 \cdot 10^8\ ms^{-1}$ | $10^6\ ms^{-1}$ |
| **Snell-Descartes** | $n_1 sin\theta_1 = n_2 sin\theta_2$ | $E_{F1} sin\theta_1 = E_{F2} sin\theta_2$ |
| **Critical angle** | $\theta_c = \arcsin\left(\frac{n_2}{n_1}\right)$ | $\theta_c = \arcsin\left(\frac{E_{F2}}{E_{F1}}\right)$ |
| **Fresnel relation** | $R_s = \left\lvert\frac{n_1 cos\theta_i - n_2 cos\theta_t}{n_1 cos\theta_i + n_2 cos\theta_t}\right\rvert^2$ | $T(\theta) = e^{-\pi\frac{2d}{\lvert k_1 - k_2\rvert}k_2^2 \sin^2\theta}$ |

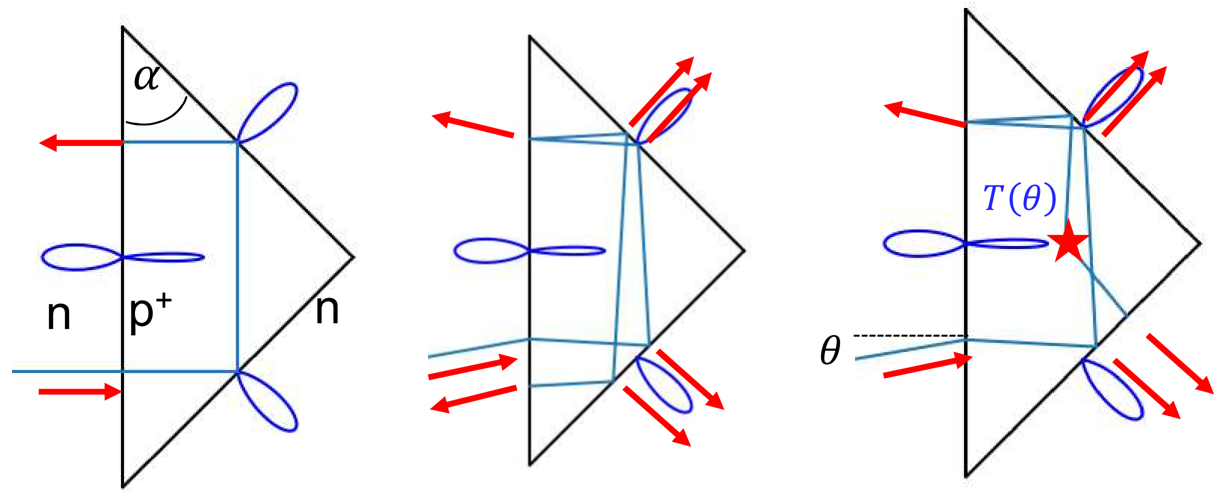
Cheianov et al., PRB **74** (2006) 041403(R) J. Cayssol et al., PRB **79** (2009) 075428

# Dirac Fermion Reflector (DFR)

**Transmission probabilities**



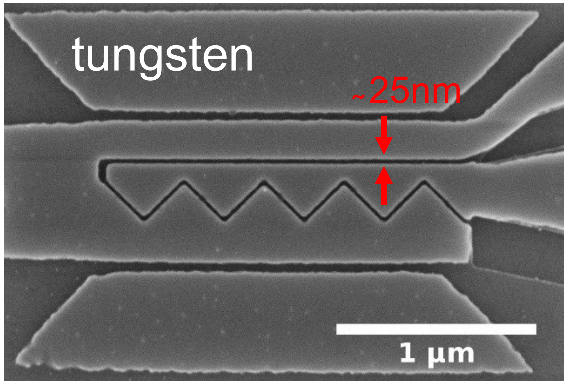

**Dirac fermion reflector**




Q. Wilmart et al., 2D Mat. **1** (2014) 11006

**Bicycle photon reflector**

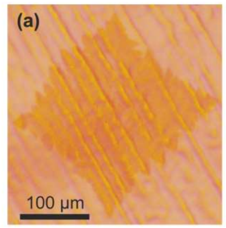
# Sample fabrication

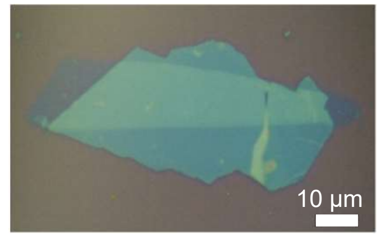



## nano-patterned bottom gates

- gold or tungsten
- made using EBL+RIE
- independent control of $E_{F1}$ and $E_{F2}$
- sharp junction $k_F d \lesssim 1$
- small device $L < l_{mfp}$

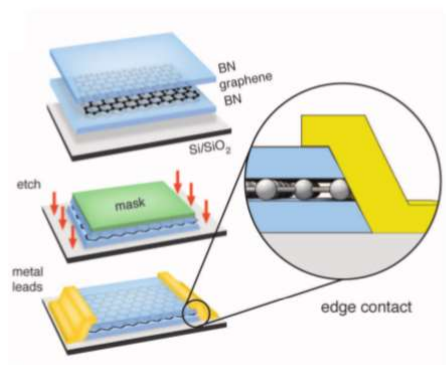
## monocrystalline CVD graphene encapsulated in exfoliated hBN



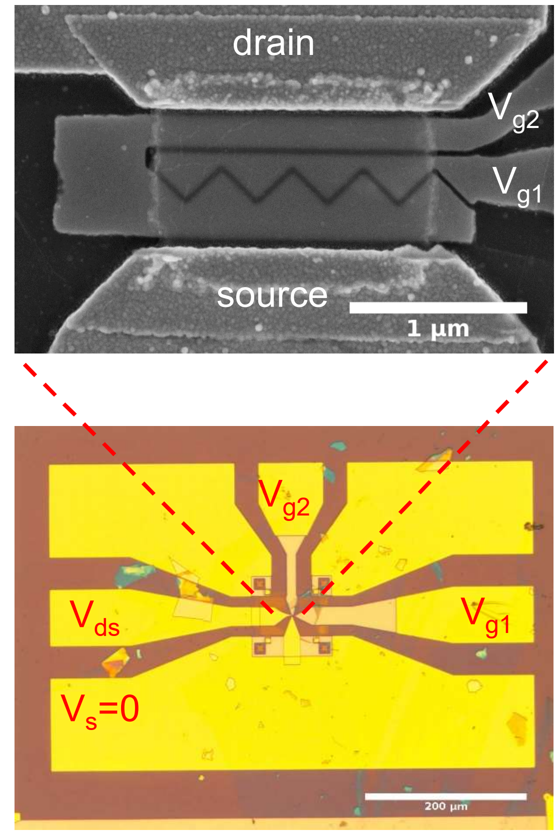




L. Banszerus et al.,
Nano Lett. **16** (2016) 1387

## etching + 1D edge contact




## final sample

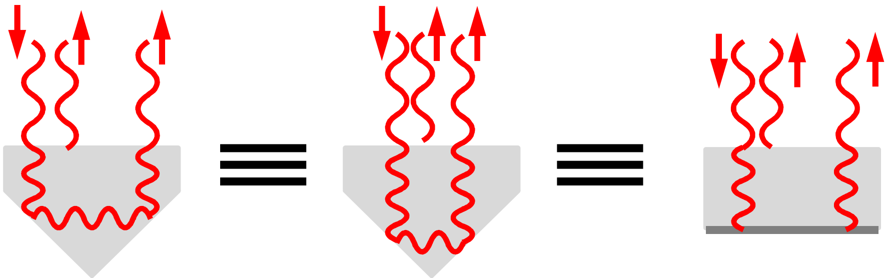


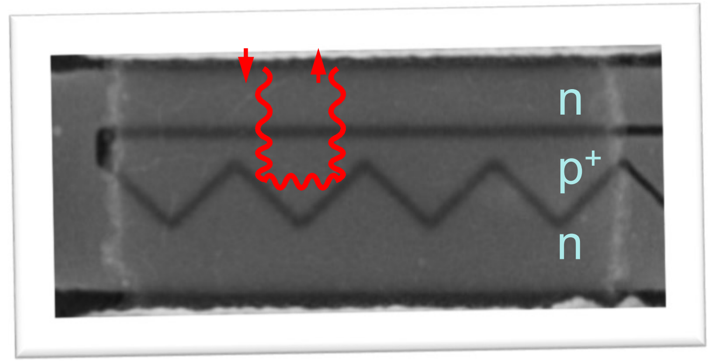

Morikawa et al., Semicond. Sci. Technol. **32** (2017) 045010
20° opening angle, top-bottom gate approach:

Wang et al., Science **342** (2013) 614

- nano-patterned bottom gates ensure precise control of the refractive index
- high-quality encapsulated graphene ensures long mean free path

# "Fabry-Pérot" oscillations (coherent DFO) at 6 Kelvin



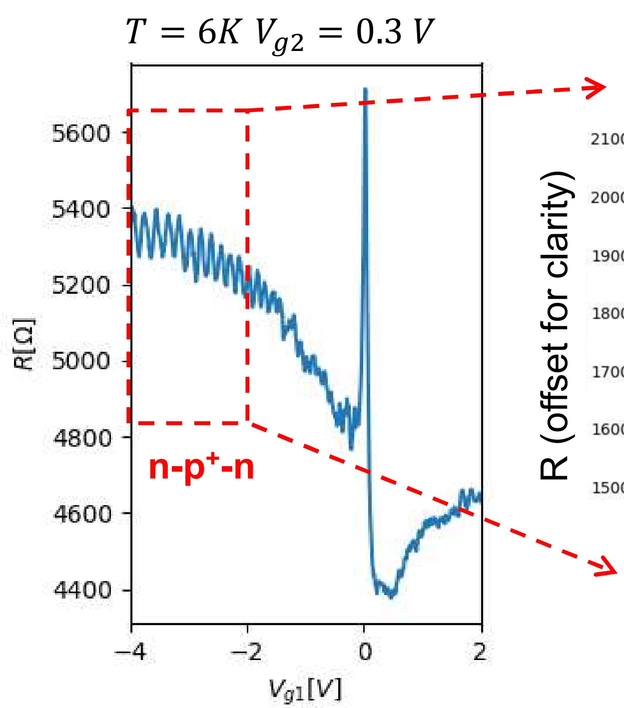


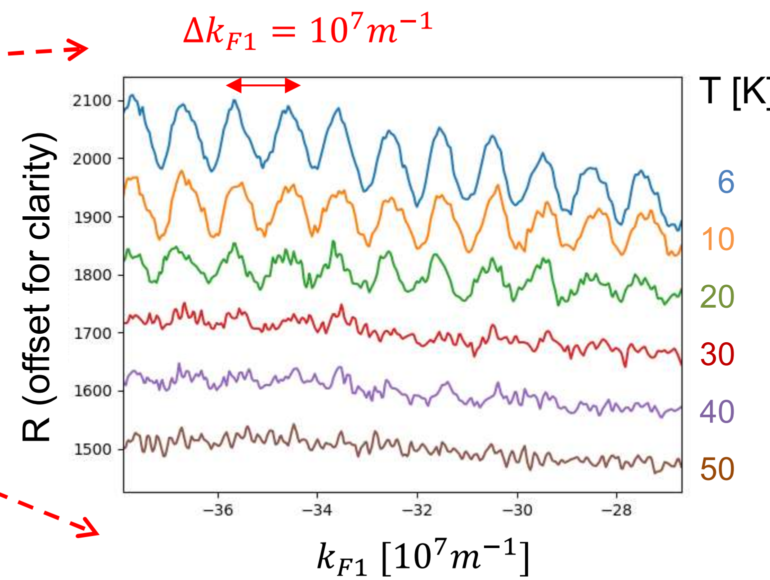

Calibrate gate coupling, so that:

$$L = \frac{2\pi}{\Delta k_{F1}} = 600\ nm$$

Oscillations disappear around:

$$T_{smear} = \frac{h v_F}{2 k_B \cdot 600nm} = 40\ K$$

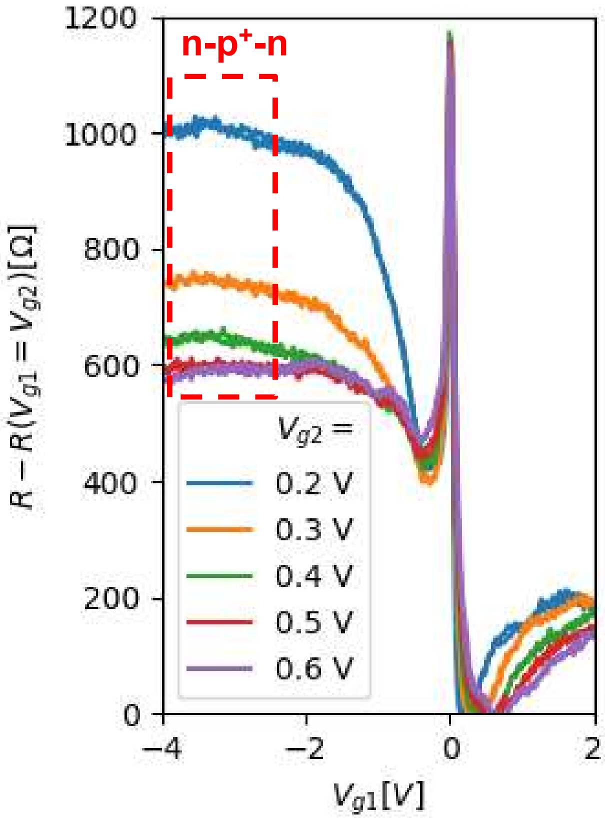



➢ Calibration of the DFR dwell length at 600 nm

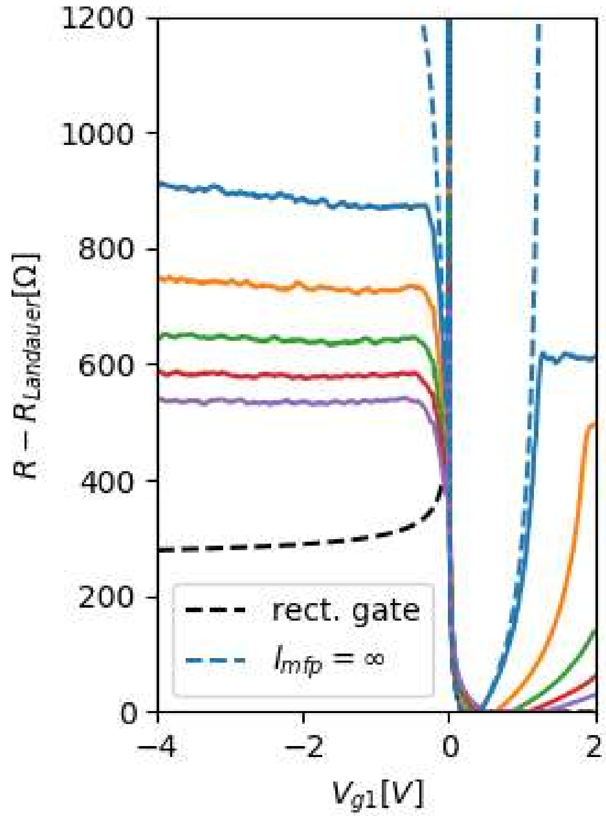
# Dirac fermion reflector (geometric DFO) at 60 Kelvin

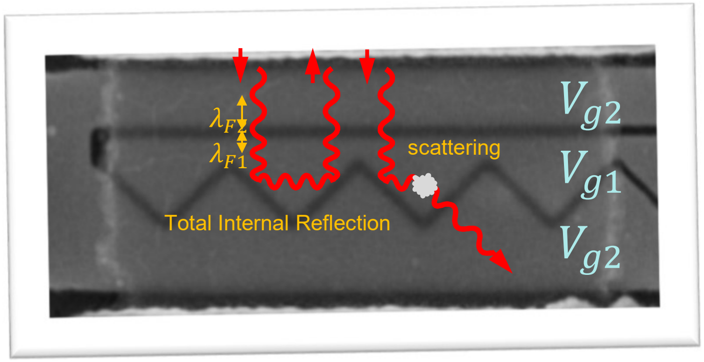
## DC experiment at 60K




## Scattering simulation

$l_{mfp} = 2.4\ \mu m$

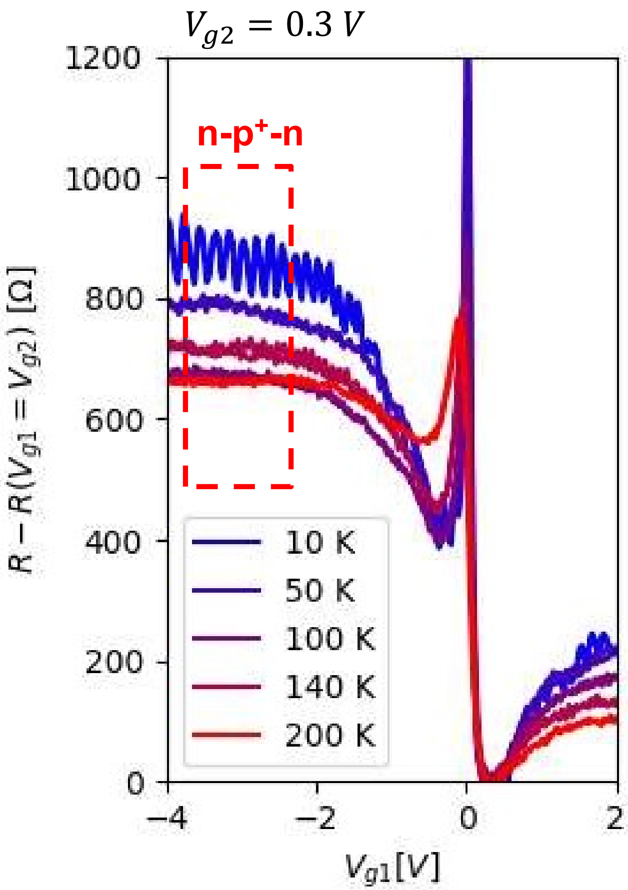


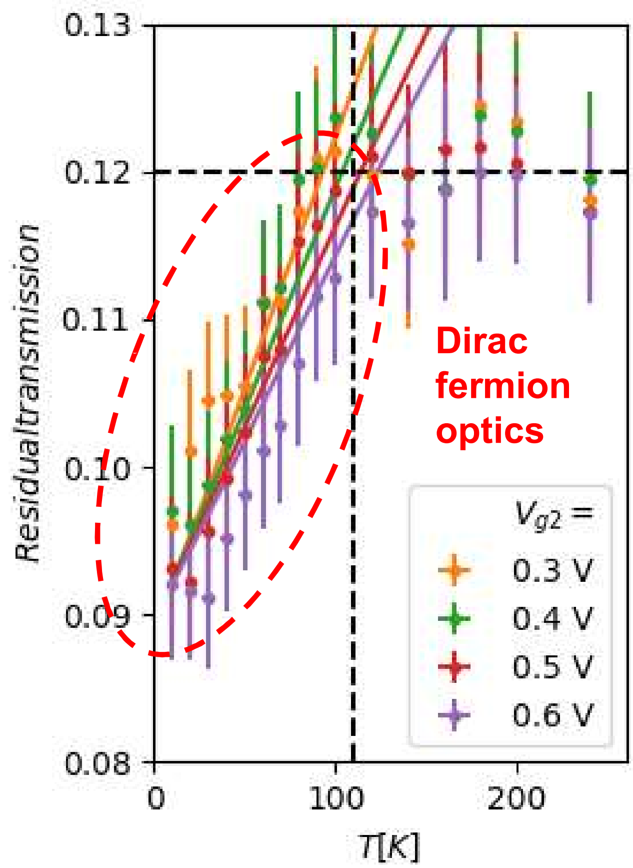




- in situ tuning of the DFO refractive index
- up to $E_{F1}/E_{F2}$=-4.8 ($\theta_c = 12°$)
- c.f. diamond/air: 2.4

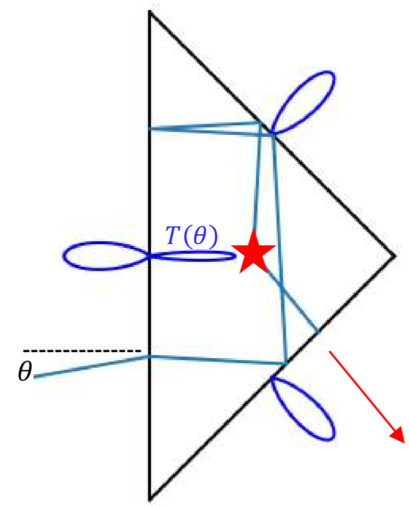
- DFR = resistance plateau in the n-p+ regime
- also works at 10 GHz

# Effect of acoustic phonon scattering




$$\frac{1}{R} = \frac{4e^2}{h}\frac{k_{F2}W}{\pi} < T(\theta) >_\theta$$




$$l_{phonon} = \frac{300\ K}{T} \cdot 800\ nm$$

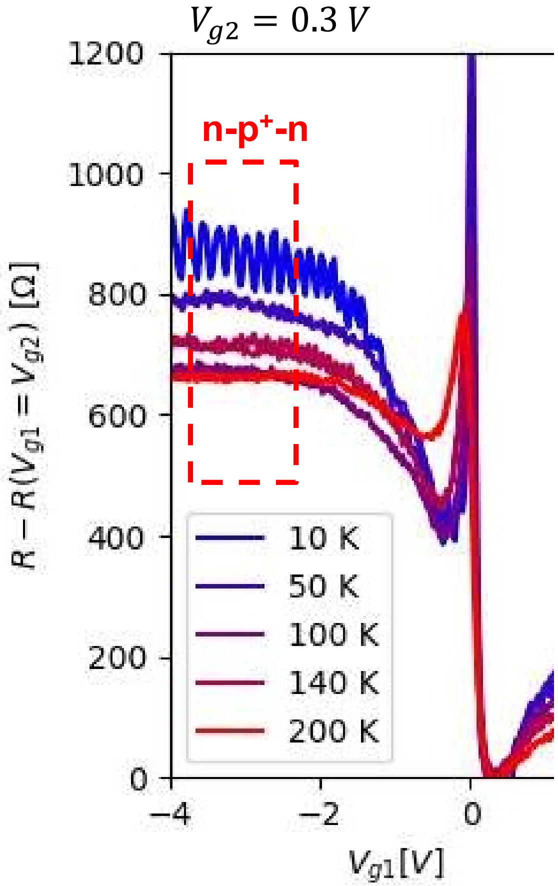
Hwang & Das Sarma, PRB **77** (2008) 115449

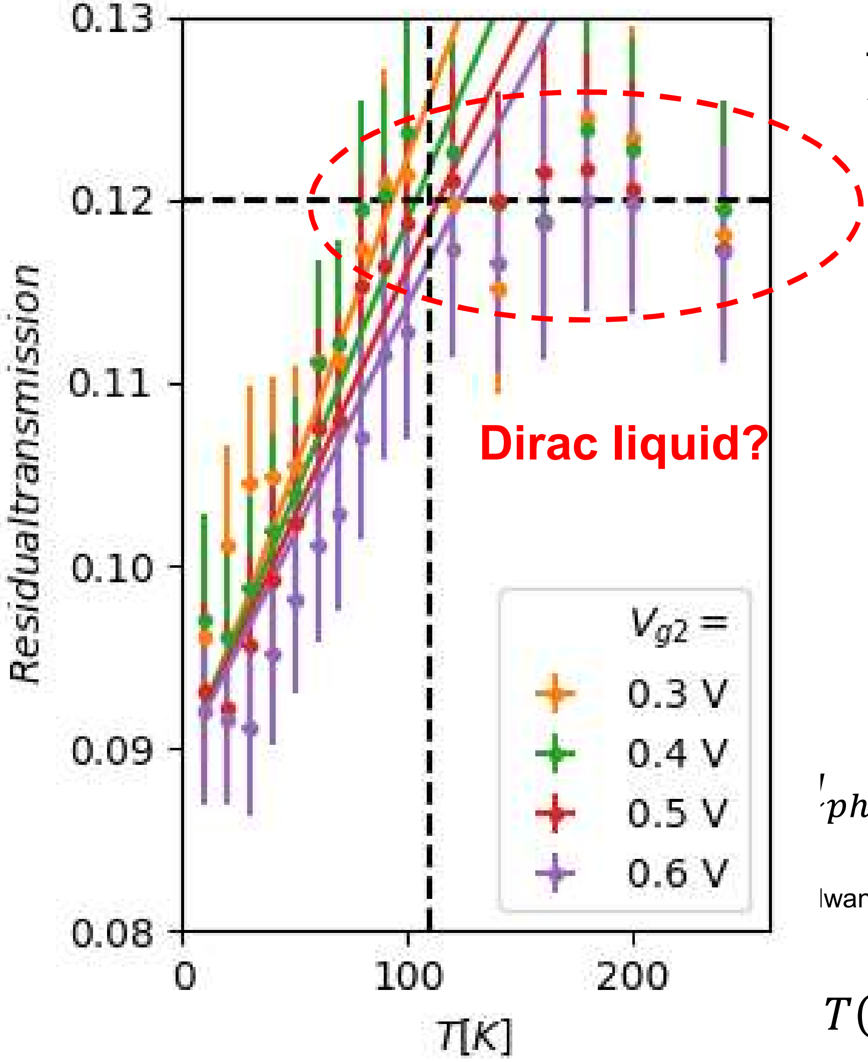
$$T_{DFR} = \int_{-\pi/2}^{+\pi/2} T(\theta)\big(1 - T(\theta)\big)^{l_{phonon}/L} \cos(\theta) d\theta$$

$$T(\theta) = e^{-\pi\frac{2d}{|k_1 - k_2|}k_2^2 \sin^2\theta}$$

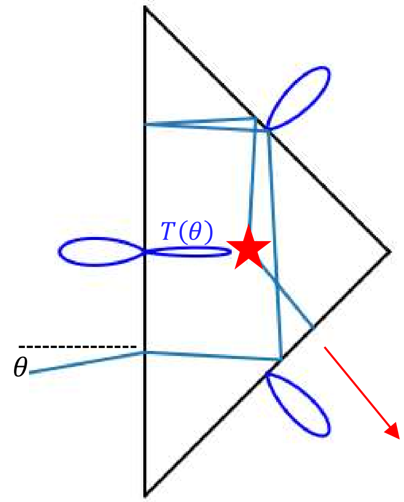
- Acoustic phonon model explains T-dependence quantitatively

# Effect of acoustic phonon scattering




$$\frac{1}{R} = \frac{4e^2}{h}\frac{k_{F2}W}{\pi} < T(\theta) >_\theta$$

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Hwang & Das Sarma, PRB **77** (2008) 115449

$$T_{DFR} = \int_{-\pi/2}^{+\pi/2} T(\theta)(1$$

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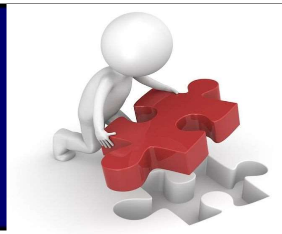
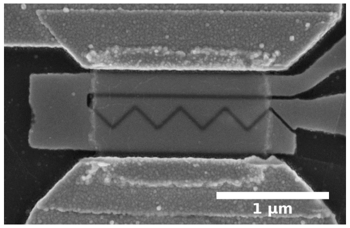
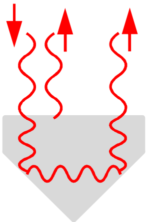
- Acoustic phonon model explains T-dependence quantitatively

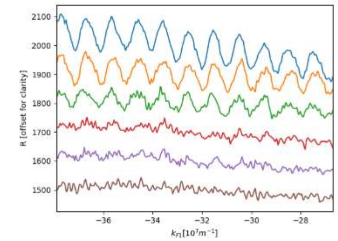


# Conclusions

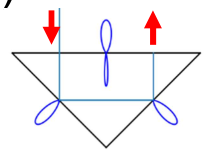


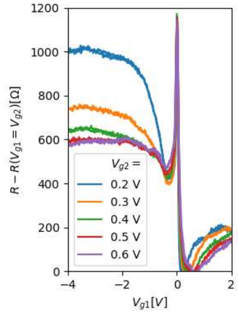

- ✓ nano-patterned gates enable local **control of DFO refractive index**

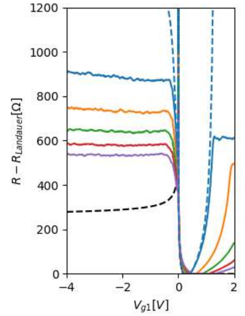




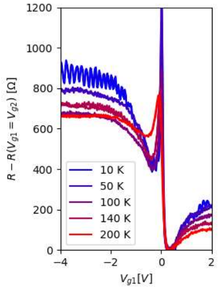
- ✓ **coherent DFO** calibrates length of the reflector

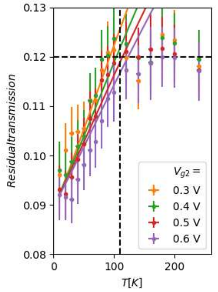





- ✓ **geometric DFO effect confirmed** (DC and 10 GHz) and in quantitative agreement with scattering simulation




- ✓ temperature dependence in quantitative agreement with **acoustic phonon scattering model**

- ✓ **viscous Dirac liquid above 100 K ?**

➢ Thank you for your attention!