Journal Club of 15.11.2024

Oliver Wicki

Interaction between Surface Acoustic Wave and Quantum Hall Effects

Xiao Liu(刘萧)[1], Mengmeng Wu(吴蒙蒙)[1], Renfei Wang(王任飞)[1], Xinghao Wang(王兴豪)[1], Wenfeng Zhang(张文锋)[1], Yujiang Dong(董昱江)[1], Rui-Rui Du(杜瑞瑞)[1,2], Yang Liu(刘阳)[1,3*], and Xi Lin(林熙)[1,3,4*]

[1] *International Center for Quantum Materials, Peking University, Beijing 100871, China*

[2] *Center for Excellence, University of Chinese Academy of Sciences, Beijing 100190, China*

[3] *Hefei National Laboratory, Hefei 230088, China*

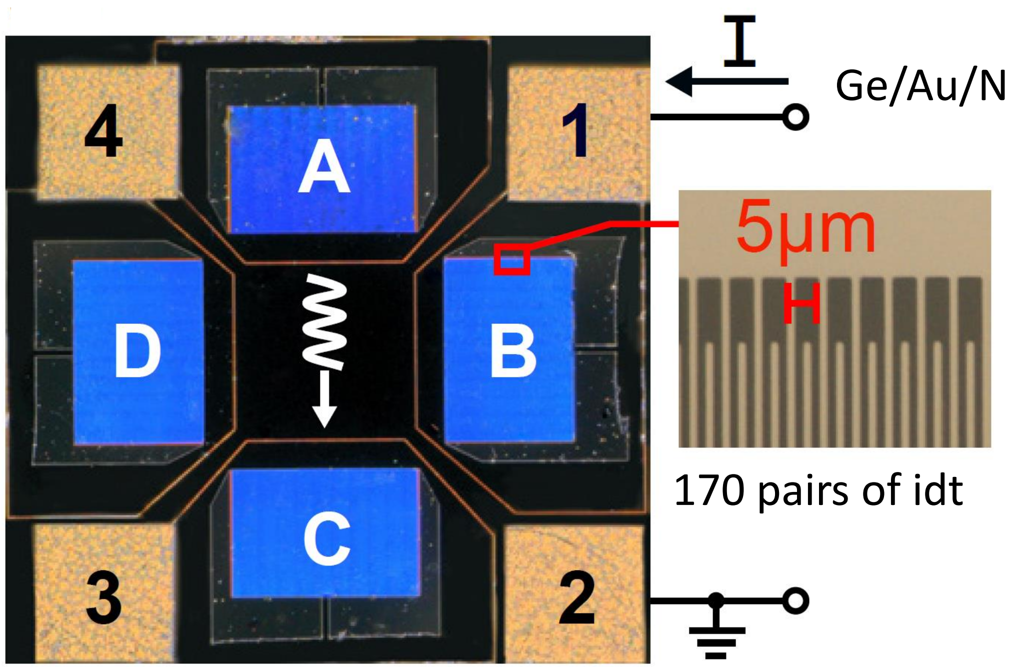
[4] *Interdisciplinary Institute of Light-Element Quantum Materials and Research Center for Light-Element Advanced Materials, Peking University, Beijing 100871, China*

(Received 7 February 2024; accepted manuscript online 21 March 2024)

Overview

- Combine surface acoustic wave (SAW) with hall bar device
- Measure interaction between 2DES and SAW by measuring velocity shift and attenuation of SAW
- How does QH-state influence SAW?
- How does the applied SAW power and current influence velocity shift and Attenuation?

Device

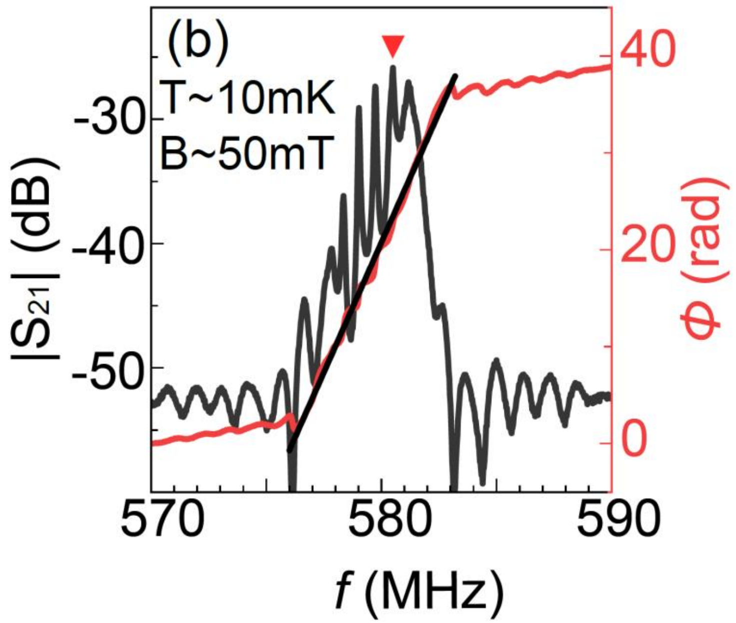


Ge/Au/Ni/Au Ohmic contacts

170 pairs of idt

SAW Wavelength: $\lambda = 5\ \mu\mathrm{m}$

Power applied to the IDT is 1nW



Measure S_{21} between A and C

resonance frequency $f_c = 580.5\ \mathrm{MHz}$

GaAs/AlGaAs heterostructure

$n = 1.12 \cdot 10^{11}\mathrm{cm}^{-2}$

$\mu \approx 10^6 \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$

2DES 120 nm below surface

2DES mesa: $1.2 \times 1.2\ \mathrm{mm}^2$

Etch 200nm

SAW velocity: $v_0 = f_c \cdot \lambda \approx 2900\ \mathrm{m\ s}^{-1}$

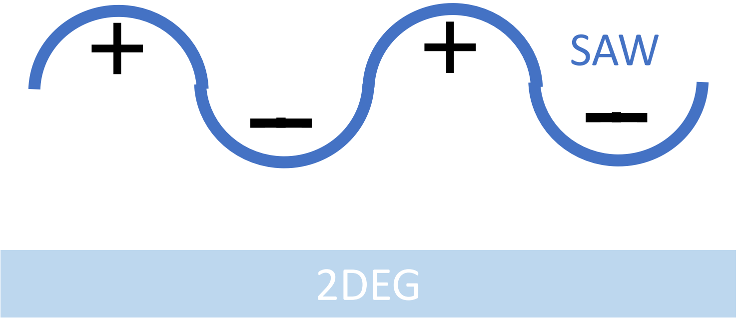
total traveling time $\tau_0 = \dfrac{\partial \phi}{\partial (2\pi f)} = 0.85\ \mu\mathrm{s}$

SAW traveling distance $d = v_0 \tau_0 \approx 2.5\ \mathrm{mm}$

Relaxation Model

SAW-2DES interact through relaxation process. Piezoelectric Field of SAW screened by 2DES electrons. → Attenuation

→ Velocity shift



Attenuation coefficient: $$\Gamma = k\frac{K_{\mathrm{eff}}^2}{2}\frac{\sigma_{xx}/\sigma_M}{1+(\sigma_{xx}/\sigma_M)^2}$$

Normalised velocity shift: $$\eta = \Delta v/v_0 = \frac{K_{\mathrm{eff}}^2}{2}\frac{1}{1+(\sigma_{xx}/\sigma_M)^2}$$

$$v_0 = v\left(\sigma_{xx} \to \infty\right)$$

Characteristic conductivity: $$\sigma_M = v_0(\epsilon) \approx 4 - 7 \times 10^{-7}\ \Omega^{-1}$$

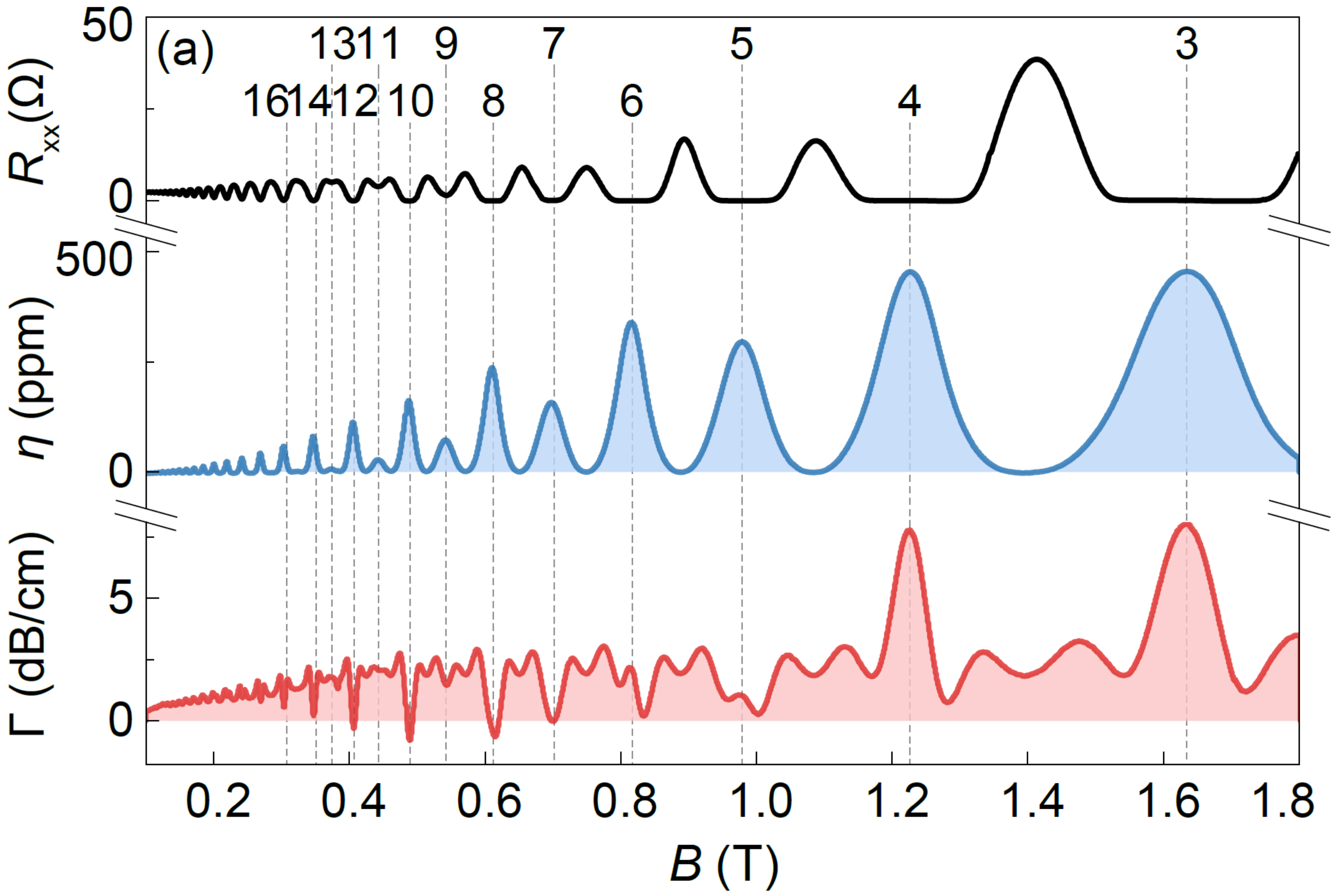
Determine velocity shift experimentally:

$$\eta = \frac{\phi}{2\pi f_c \tau}$$

SAW 2DES traveling time: $\tau \approx 0.4\ \mu s$

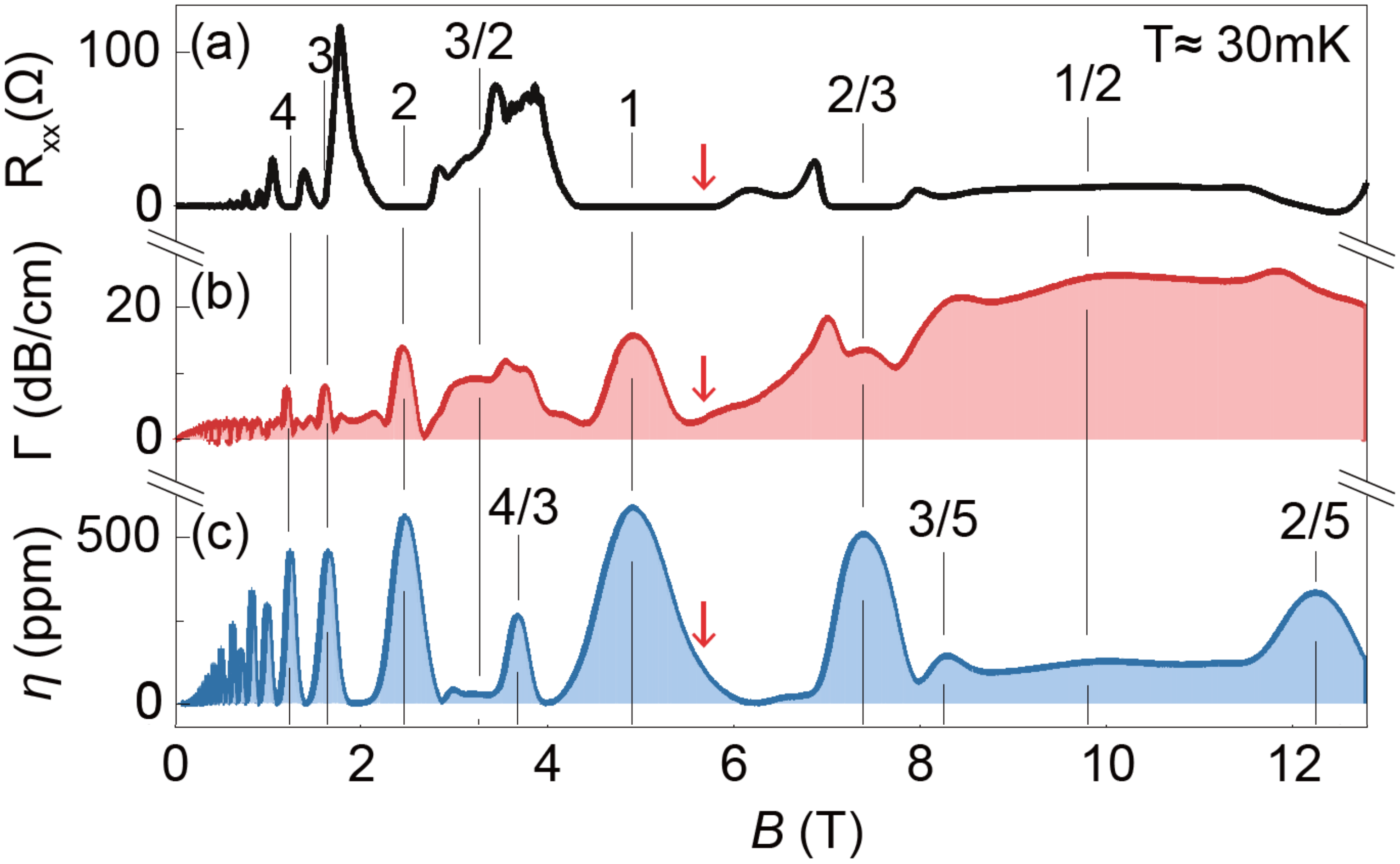
Phase : ϕ

Low-Field Measurements



- Increase in acoustic speed at integer filling factor predicted by relaxation model.
- 2DES screening capability reduces because of incompressible QH-liquid

Measurements

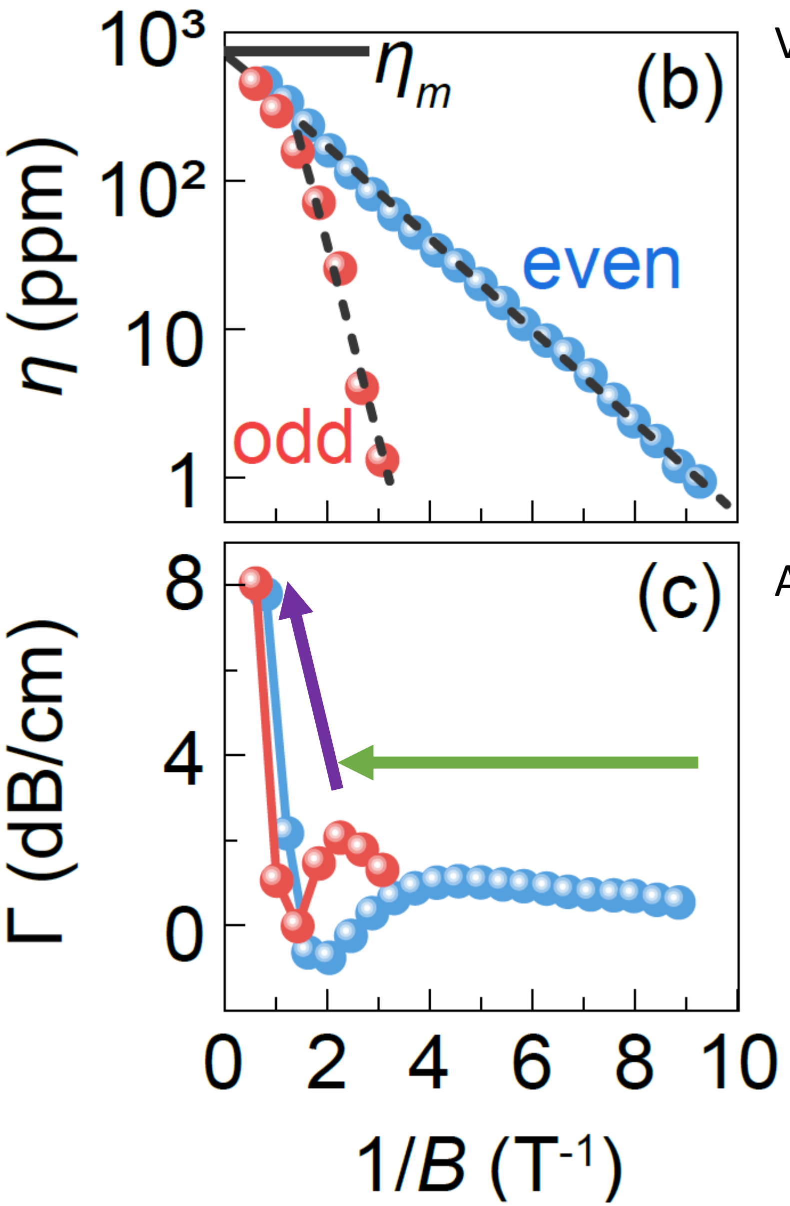


- Increase in acoustic speed at integer filling factor predicted by relaxation model.
- 2DES screening capability reduces because of incompressible QH-liquid
- At half Integer → 2DES becomes compressible →screening → slowing down SAW

Signal is better visible for η than for R_{xx}

ν =4/3 not visible in resistance measurement

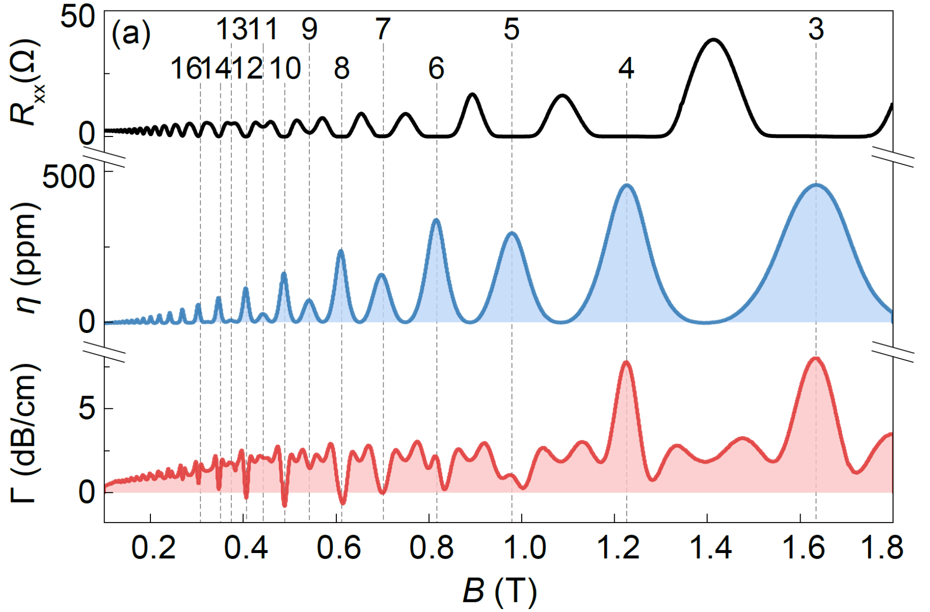
Measurements



Velocity shift at filling factor

$$\text{odd: } \eta \propto \exp\left(-\frac{\Delta_0}{E_z}\right) \;;\quad \Delta_0 = 0.9\text{ K}$$

$$\text{even: } \eta \propto \exp\left(-\frac{\Delta_e}{\hbar\omega_c}\right) \;;\quad \Delta_e = 14\text{ K}$$



Attenuation at filling factor

Increases, then decreases → Relaxation Model

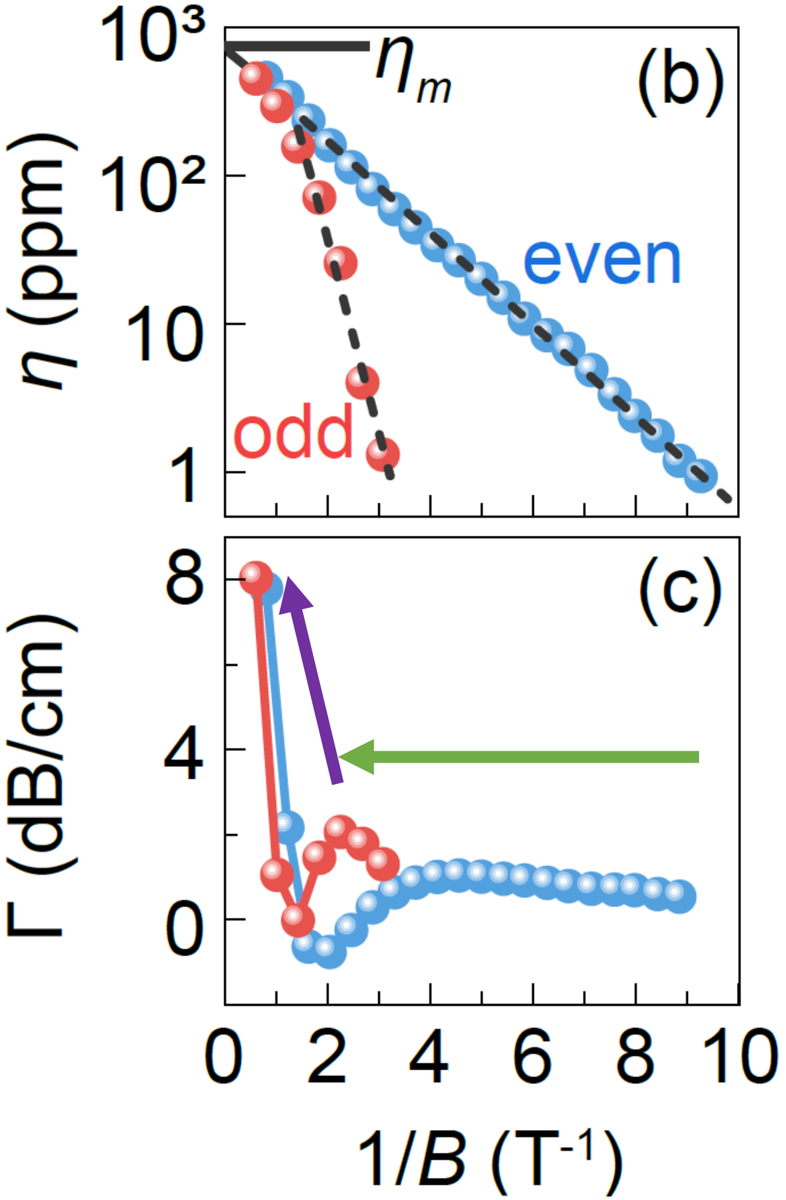
Anomalous increase

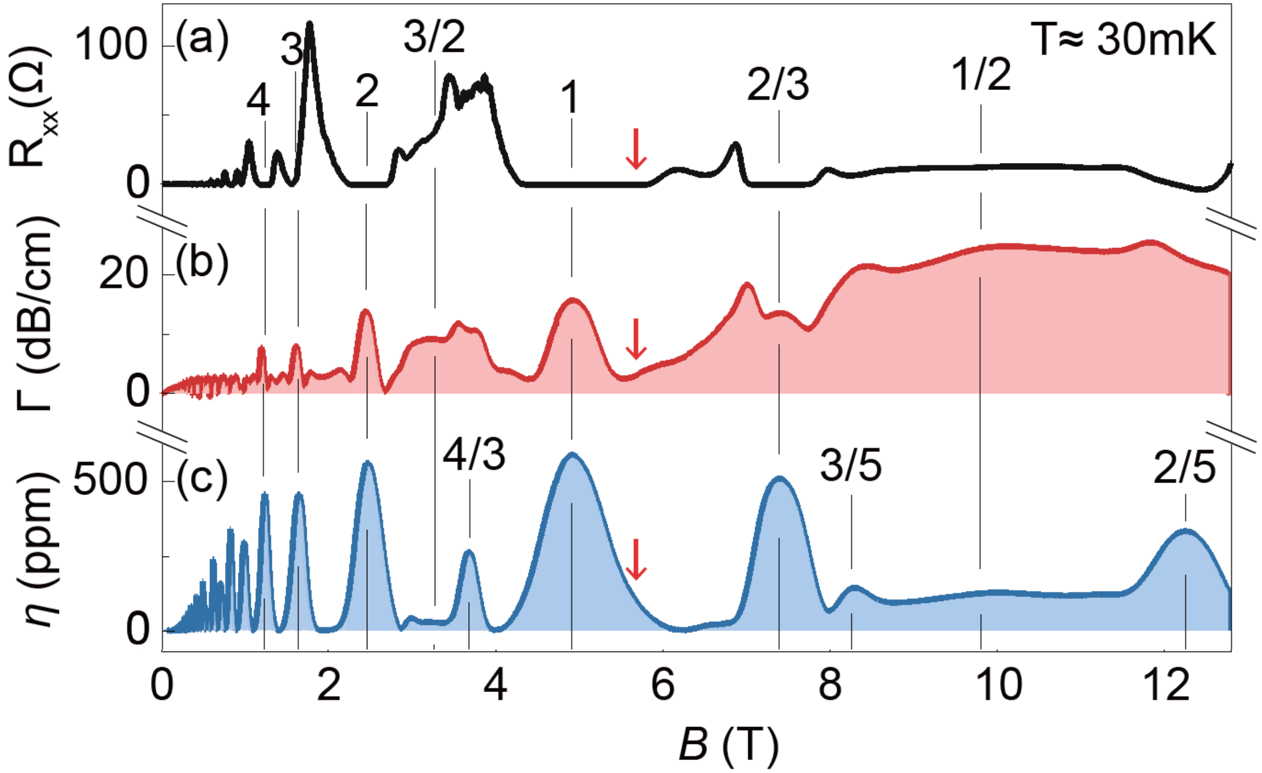
Max at $\sigma_{xx} = \sigma_M$

$$\Gamma = k\frac{K_{\text{eff}}^2}{2}\frac{\sigma_{xx}/\sigma_M}{1+(\sigma_{xx}/\sigma_M)^2}$$

- Γ increases anomalous while η increases monotonically
- Low filling factors → state more incompressible → reduced SAW-2DES interaction
- But Γ is very big at those filling factors
- Γ also big at compressible states $\nu = \frac{1}{2}, \frac{3}{2}$, while η is small

Measurements



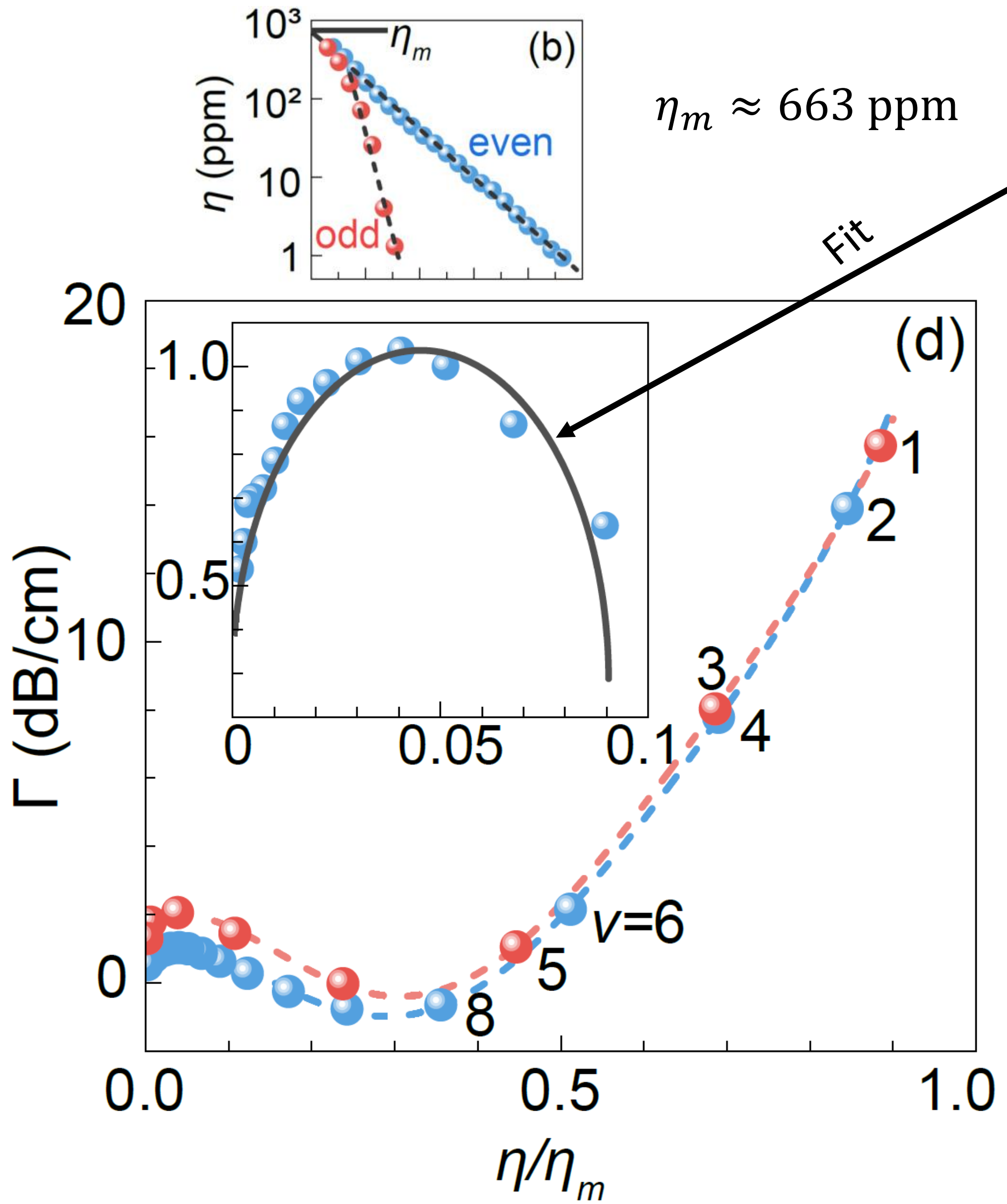


- Γ increases anomalous while η increases monotonically
- Low filling factors → state more incompressible → reduced SAW-2DES interaction
- But Γ is very big at those filling factors
- Γ also big at compressible states $\nu = \frac{1}{2}, \frac{3}{2}$, while η is small

Possible Explanation

"Emergence of correlated states which are stabilised by strong electron-electron interactions at low ν like Quantum Hall effects, composite fermion Fermi sea, Wigner crystals, etc.
These states might be effective in damping the piezoelectric field of the SAW by e.g. electron-electron scattering.
At the same time long range correlation prevents the reduction of the acoustic velocity"

Fit



$\eta_m \approx 663$ ppm

Relaxation model only valid for high filling factors

$$\Gamma = k\frac{K_{\text{eff}}^2}{2}\frac{\sigma_{xx}/\sigma_M}{1+(\sigma_{xx}/\sigma_M)^2}$$

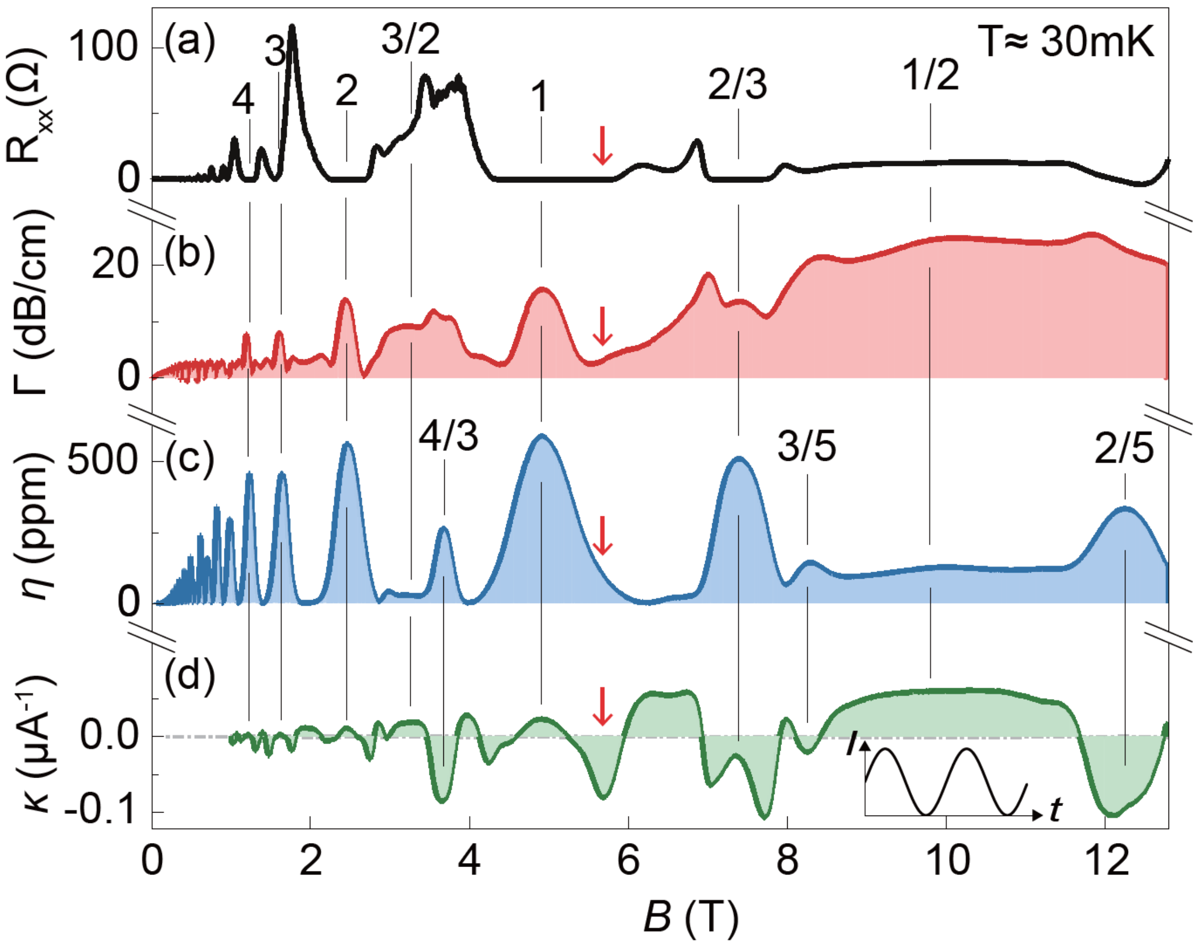
$$\eta = \Delta v/v_0 = \frac{K_{\text{eff}}^2}{2}\frac{1}{1+(\sigma_{xx}/\sigma_M)^2}$$

Using: $K_{\text{eff}}^2 = 1.2 \cdot 10^{-4}$

Behaviour near linear for low ff.
Theoretical model for SAW-2DES missing

“We hope that our clear experimental observations can help to stimulate future investigations.”

Effects of SAW power and applied current



Apply current between 1 and 2:

0.25 Hz, 400 nA peak to peak, with 200 nA offset

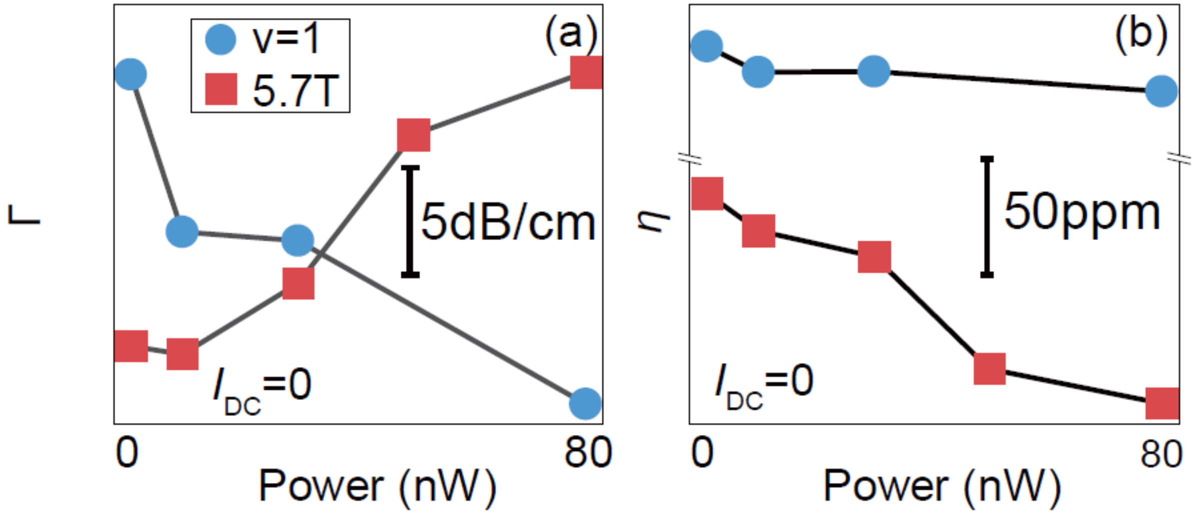
Resulting change in velocity shift represented by: $\kappa = \eta_m^{-1} \cdot \frac{\partial \eta}{\partial |I|}$

Strong QHE →κ approaches 0

Fragile QHE →κ becomes negative → current makes 2DES more efficient in slowing down acoustic wave

Happens at edges of R_{xx} plateaus. (arrow)

SAW Power

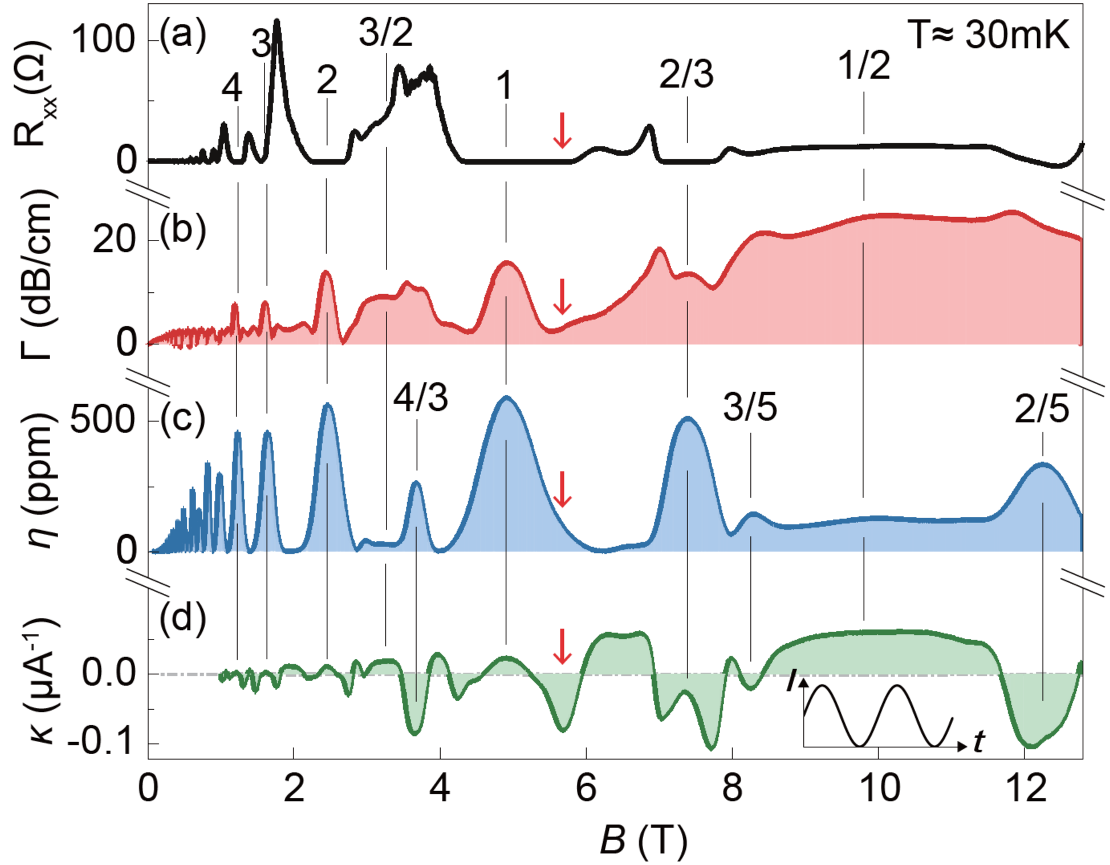


Results only visible with very low power

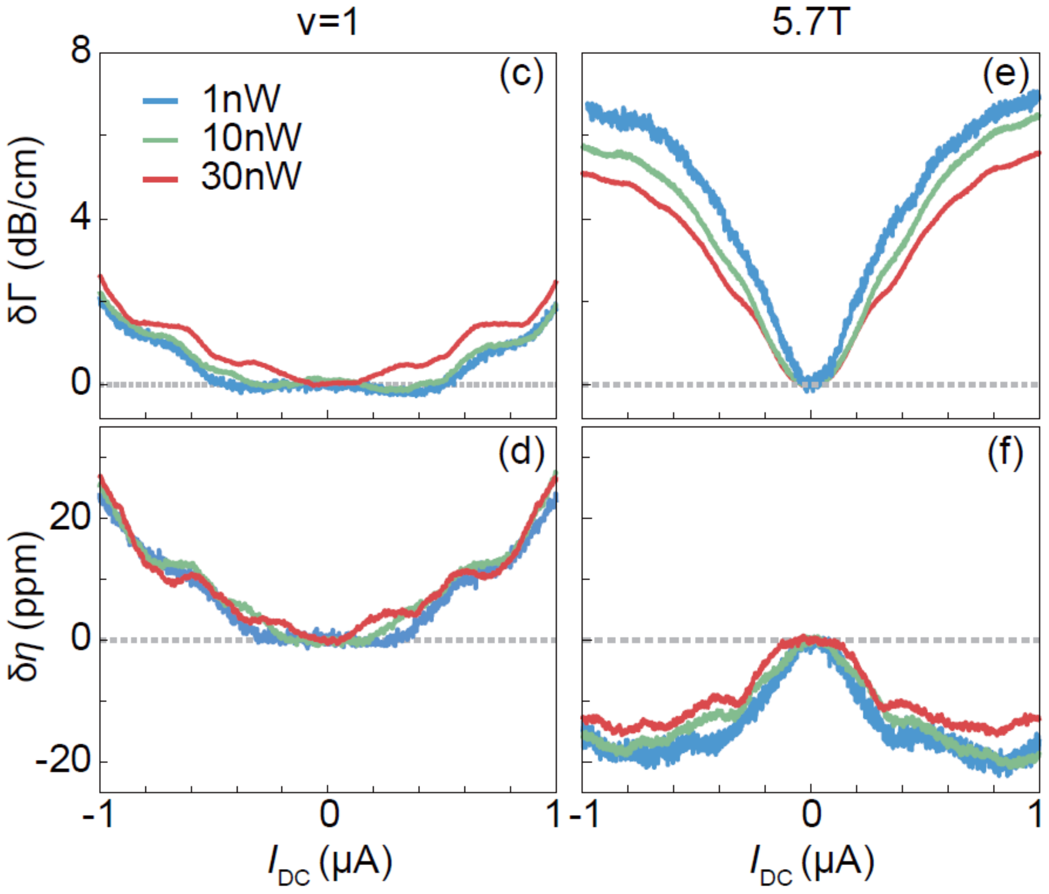
Conducting current changes Attenuation and velocity shift

Anomalous peak at $\nu = 1$ only visible at low SAW amplitude

Increasing Power reduces η



Current



$\delta\Gamma = \Gamma(I) - \Gamma(0)$

$\delta\eta = \eta(I) - \eta(0)$

Current induced change

Increasing current increases Γ and η at $\nu = 1$

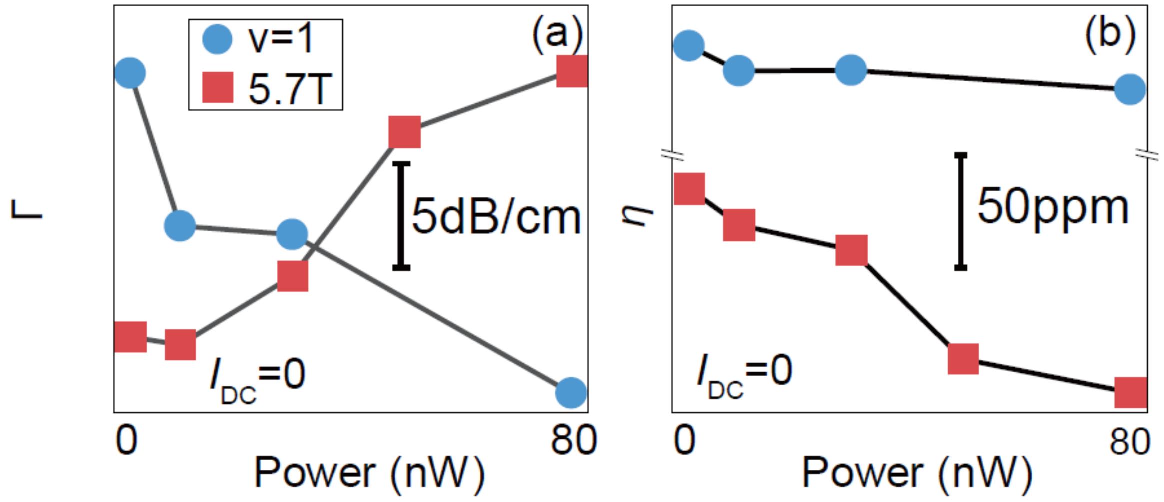
Threshold current of 300 nA for low SAW power at $\nu = 1$

Increasing SAW power and increasing current have opposite effects $\nu = 1$

But have qualitatively the same outcome at $5.7\ \mathrm{T}$

Changes saturate at $I > 700\ \mathrm{nA}$ at $5.7\ \mathrm{T}$, $I > 2\ \mu\mathrm{A}$ at $\nu = 1$

Which is less than the breakdown current for $\nu = 1$



Conclusion

4. CONCLUSION

Our systematic study shows that the conventional relaxation model is insufficient in describing the SAW-2DES interaction at very low SAW power and when 2DES forms strongly correlated states. We present as much experimental evidence as possible, and hope a comprehensive theoretical models can be proposed in the future.

Summary

- **SAW-2DES interaction:** Demonstrate SAW as a non-invasive and sensitive probe for quantum states in a 2DES
- **Attenuation and Velocity shift:** measure the Attenuation and velocity shift to show changes in compressibility of the 2DES and get better visible data than for the resistance measurement
- **Interaction energy determination:** extract interaction energy from velocity shift fit: $\Delta_0 = 0.9\ \mathrm{K}\,;\ \Delta_e = 14\ \mathrm{K}$
- **Relaxation Model:** For high filling factors, the data agrees with the relaxation model
- **Anomalous behaviour:** For low filling factors, the data behaves very differently → relaxation model not applicable
- **SAW power and applied current:** Effect of different SAW power and different strengths of applied current on the Attenuation and velocity shift were investigated.
- **Low SAW power:** The described effects are only visible with sufficiently low SAW Power.

END