Quantum transport phenomena in quantum wells of a topological crystalline insulator (Pb,Sn)Se

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Abstract / Summary

No quantized charge transport via helical or chiral edge states has been experimentally demonstrated for the topological crystalline insulators. Here, we grew by MBE high crystalline quality $Pb_{1-x}Sn_xSe$:Bi/$Pb_{1-y}Eu_ySe$ QWs with x = 0.25 and y = 0.1 and thicknesses between 10 and 50 nm, then we thoroughly characterized their low-temperature magnetotransport properties, i.e. WAL, UCF, SdH, and QHE. These results, together with multiband k·p modelling, have enabled us to assess valley degeneracies, the magnitude of strain, subbands effective masses, the Berry phases, and the topological phase diagram as a function of the QW thickness. Our work demonstrates that further progress in controlling Sn content, carrier densities, and magnetism would allow exploration of the topologically protected quantized edge transport even in the absence of an external magnetic field.

Introduction

Topological crystalline insulators:

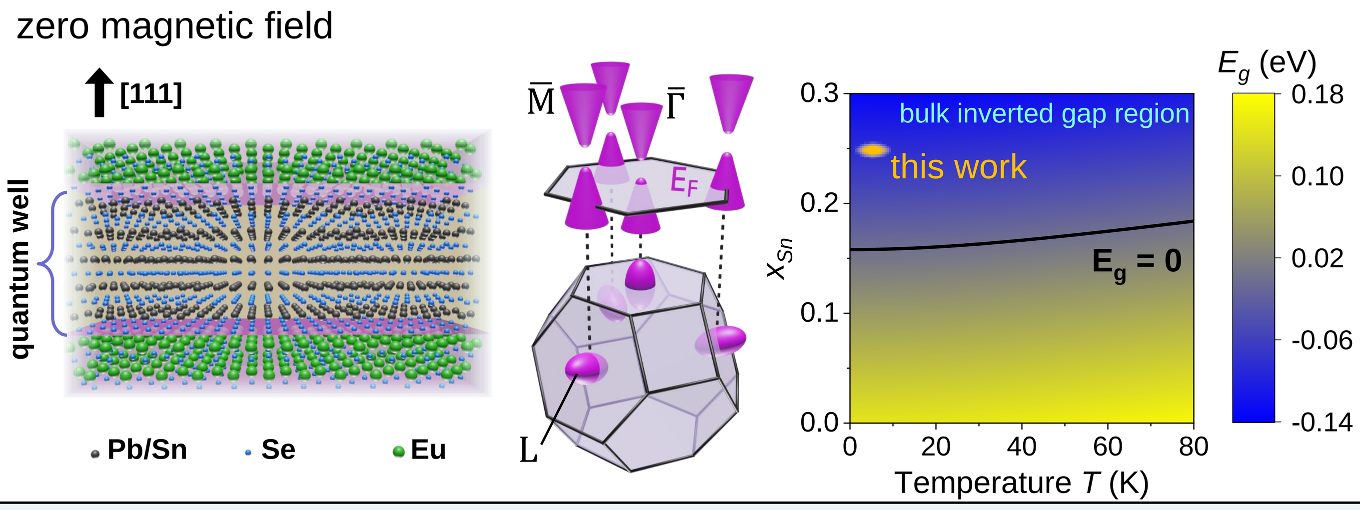
Topological surface states (TSS) are protected by the (110) mirror plane symmetry; no QHE or QSHE or QAHE so far; intriguing behavior: SU(3) QH ferromagnetism; valley polarized QHE states

Material:

IV-VI semiconductors: $Pb_{1-x}Sn_xTe$ (x>0.4) or $Pb_{1-x}Sn_xSe$ (0.4>x>0.15); barriers for the QW structure $Pb_{1-y}Eu_yTe$ or $Pb_{1-y}Eu_ySe$; barriers create strain, which lead to partial lifting of valley degeneracy for (111) QWs

Goal:

Study the potential of PbSnSe/PbEuSe QWs for topological edge transport in zero magnetic field



Samples

Epitaxial Growth

Molecular beam epitaxy (MBE) of $Pb_{0.75}Sn_{0.25}Se/Pb_{0.9}Eu_{0.1}Se$ QWs has been carried out on (111) BaF_2 substrates using a Riber 1000 MBE system. The growth utilized compound PbSe and SnSe and elemental Eu and Se as the source materials. To achieve low carrier densities, extrinsic n-type Bi-doping (nominally 0.004%) is introduced using a Bi_2Se_3 doping cell.

Grown structures

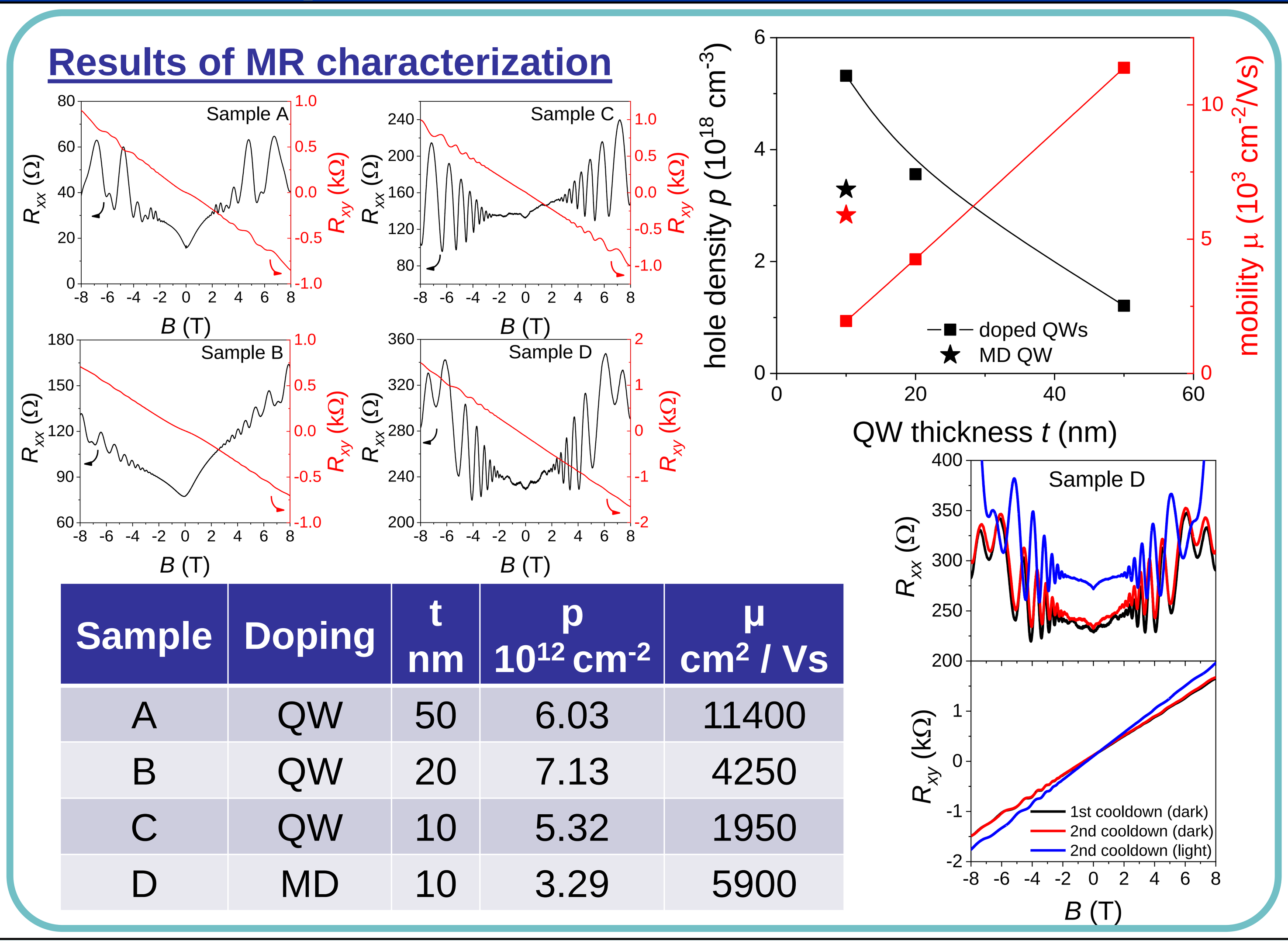
Doped QWs

- $PbEu_{11}Se$ 200 nm
- QW $PbSn_{25}Se$+BiSe
- $PbEu_{11}Se$ 2 μm
- BaF_2 (111)

Modulation doped QWs

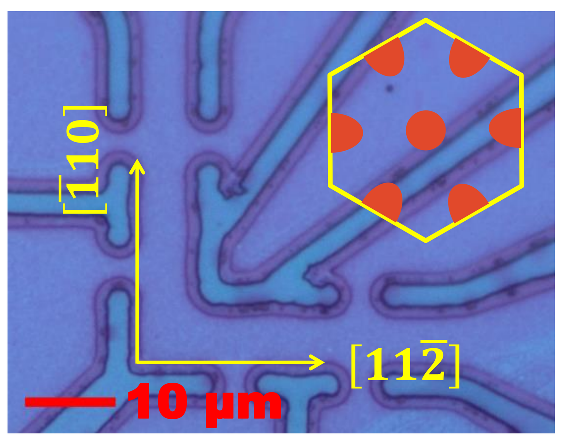
- $PbEu_{11}Se$ 200 nm
- $PbEu_{11}Se$+BiSe 10 nm
- $PbEu_{11}Se$ 5 nm
- QW $PbSn_{25}Se$ 10 nm
- $PbEu_{11}Se$ 5 nm
- $PbEu_{11}Se$+BiSe 10 nm
- $PbEu_{11}Se$ 200 nm
- $PbEu_{11}Se$ 3 μm
- BaF_2(111)

Results of MR characterization

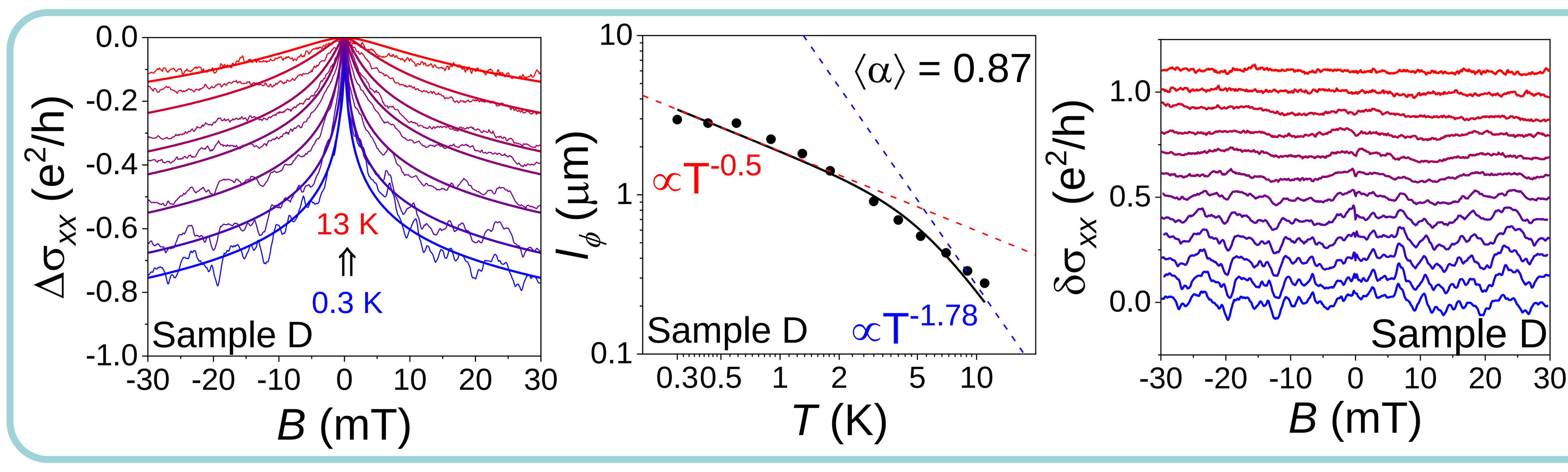


Sample	Doping	t nm	p 10^{12} cm^{-2}	μ cm^2 / Vs
A	QW	50	6.03	11400
B	QW	20	7.13	4250
C	QW	10	5.32	1950
D	MD	10	3.29	5900

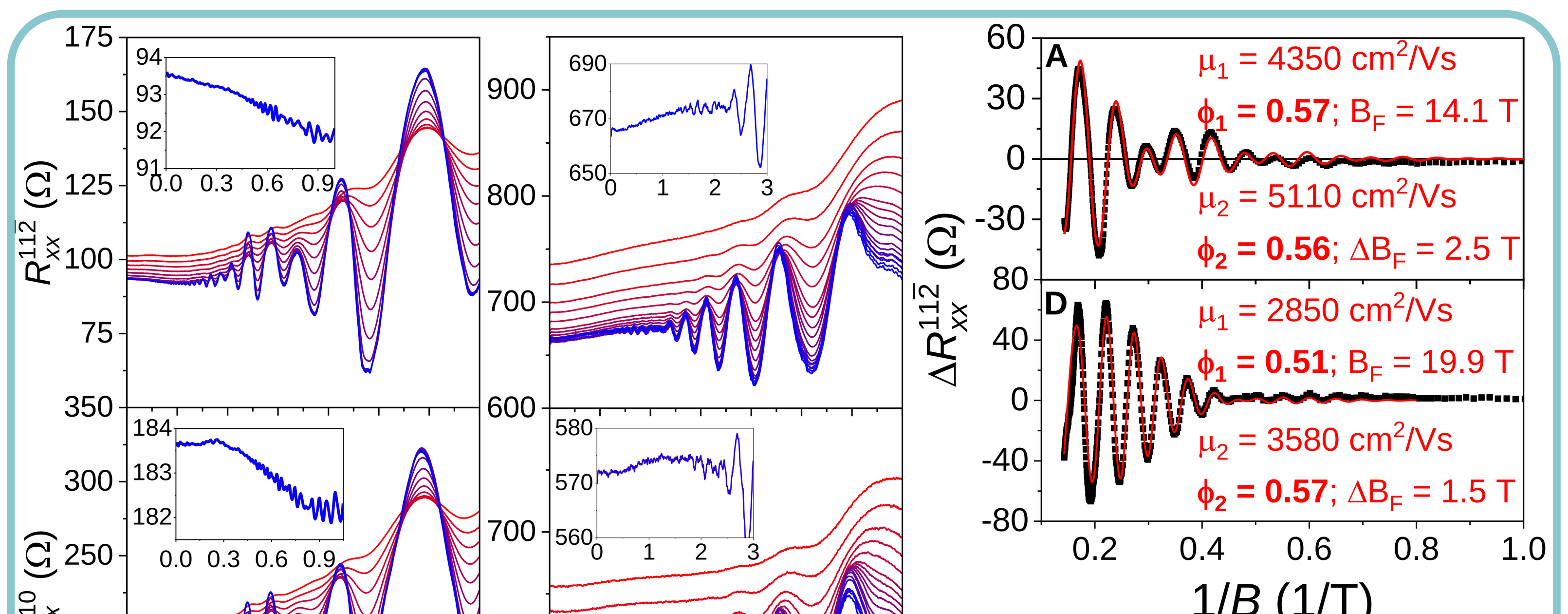
Results



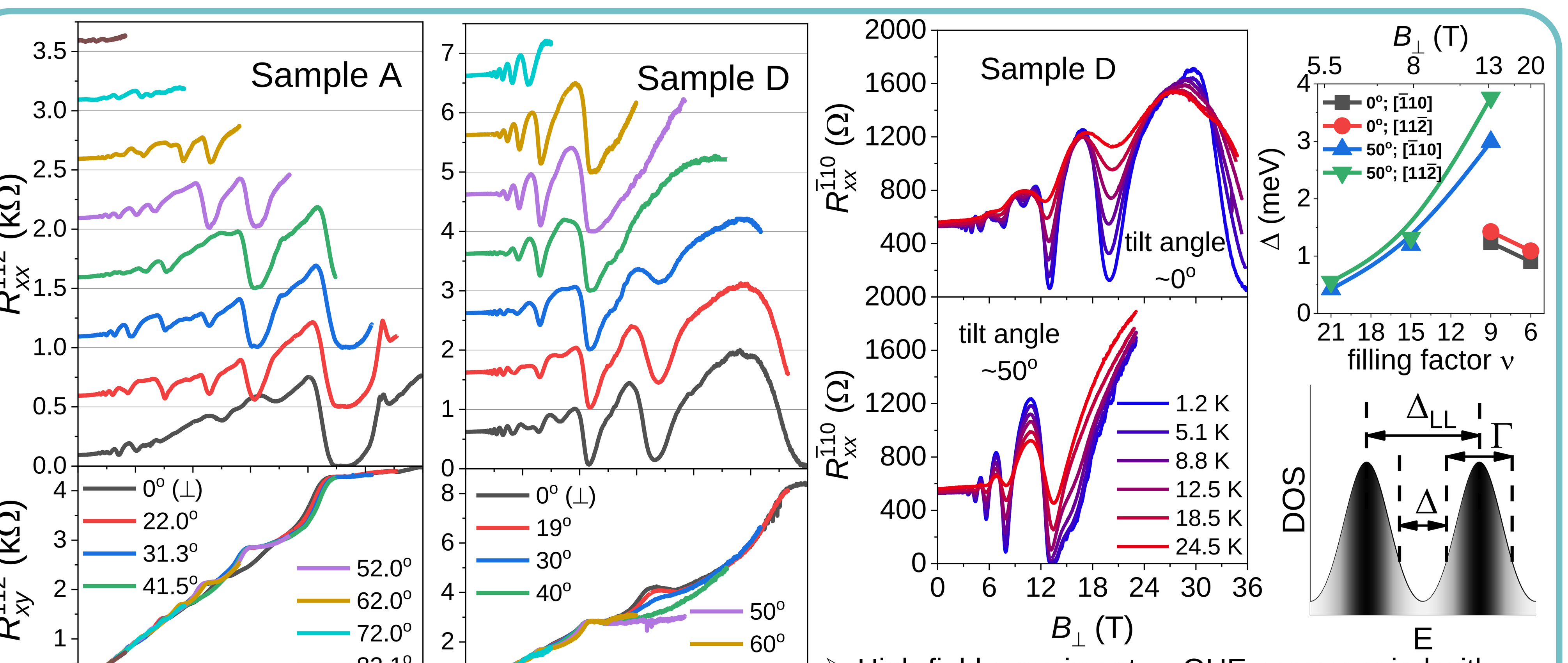
QWs were processed into L-shaped Hall bar structures, using optical lithography and wet Br etching techniques. This configuration allows for a comparison of transport properties in $B_\perp$ and $B_\parallel$ when the current is applied either perpendicular or parallel to one of the oblique valleys.



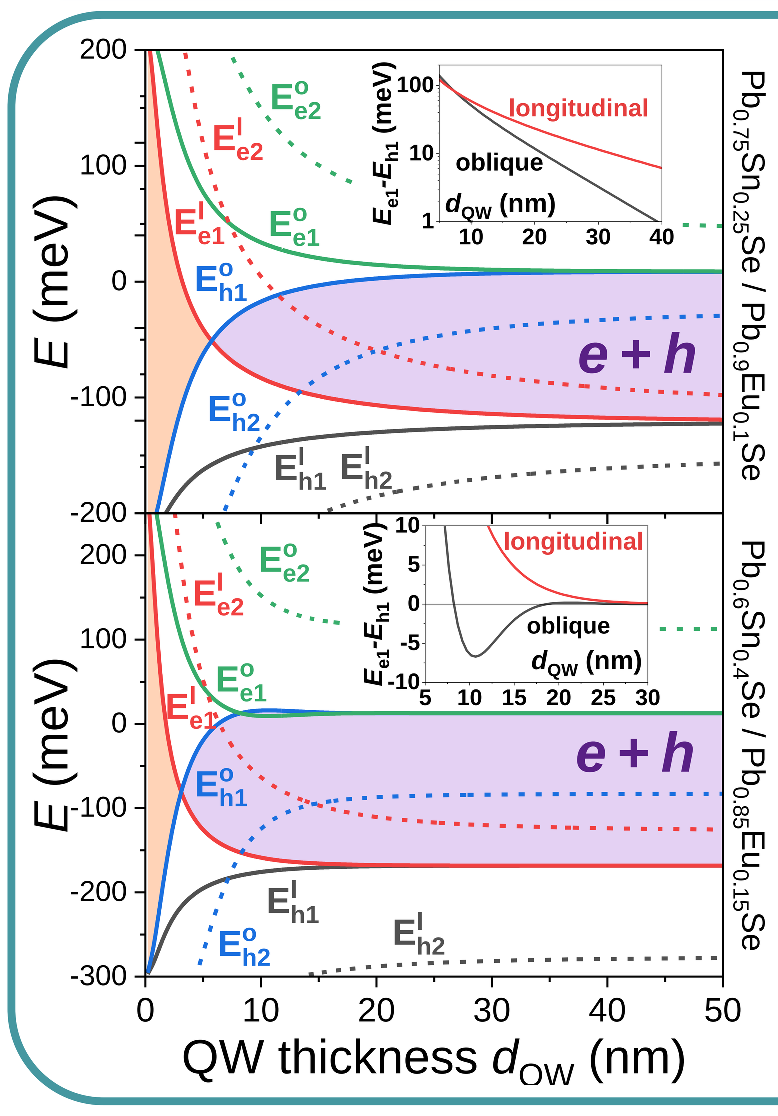
The character of weak antilocalization magnetoresistance and universal conductance fluctuations points to a long phase coherence length. A relatively large magnitude of the dielectric constant is responsible for a weak decoherence by electron-electron scattering in IV-VI compounds.



- SdH oscillations start from 0.5 – 2 T → high-quality of the grown QWs
- Observed decrease in both Hall and quantum mobilities with t → the critical role of the QW/barrier interfaces
- SdH beating and doubling of FFT peak → two occupied subbands (A) or low-field spin-splitting from both exchange and large SOC (B-D)
- Fitting temperature damping of FFT peak → cyclotron mass of ~0.15m_0
- Fitting low field SdH with two cosines → quantum mobility and phase of quantum oscillations



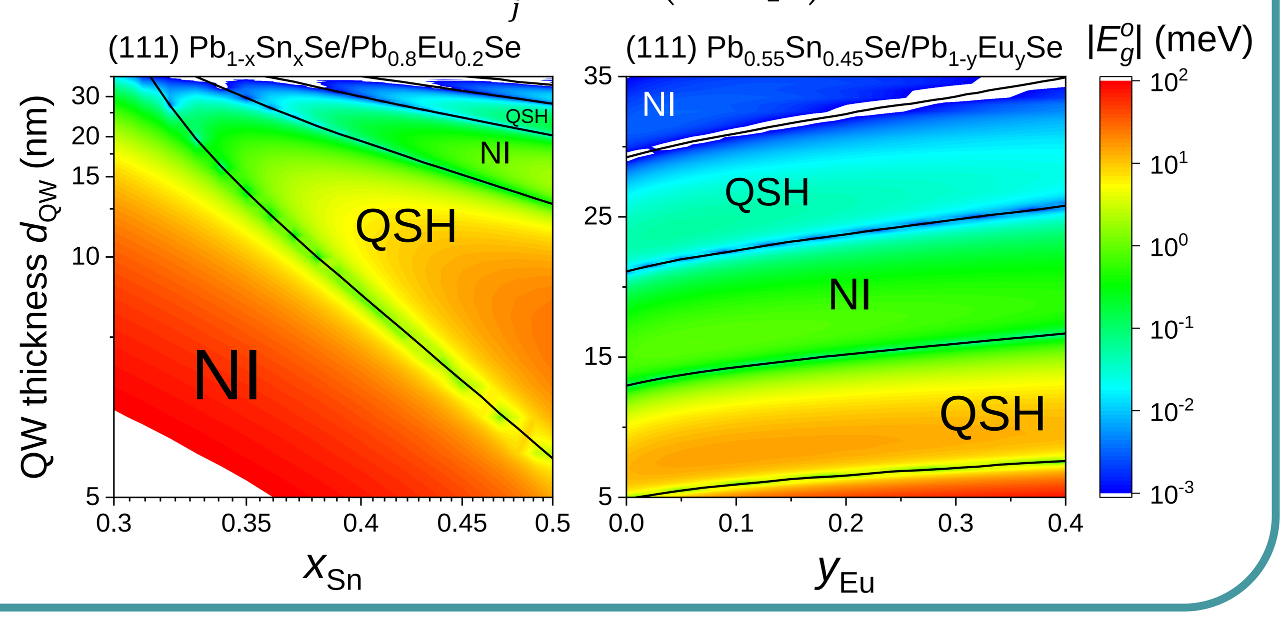
- High-field experiment → QHE accompanied with zero-resistance states
- QHE filling factors are multipliers of 3 → only M valleys are contributing to QHE
- Significant evolution of the QHE states with tilting
- Phase of the QHE states is close to 0
- Temperature dependence of QHE states → energy distance between tails of the broadened LLs
- Large LL broadening → agreement between Δ, $Δ_{LL}$ and Γ

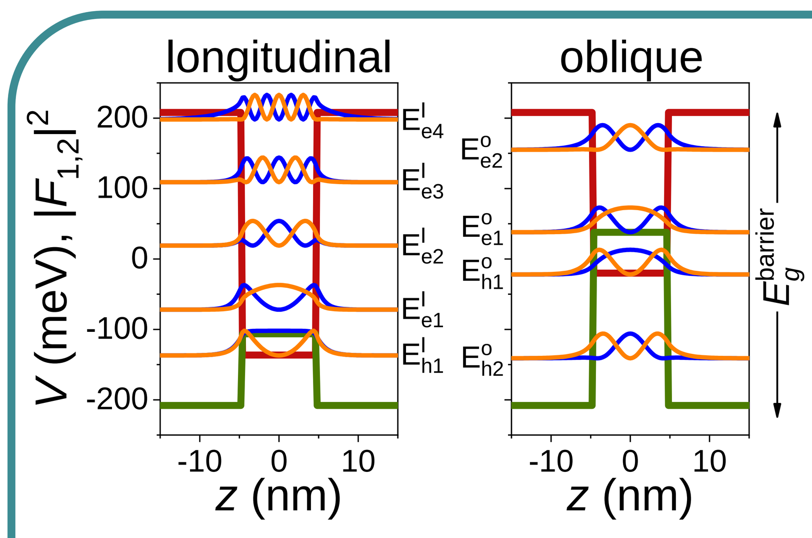


- We've employed a Mitchell-Wallis 4-band k·p Hamiltonian $\hat{H}$. Also accounted exchange interaction in the valence band arising from the barriers.
- Used band parameters for pure PbSe. Only bandedges are changed over the QW/barrier interface
- Schrödinger equation is solved separately for longitudinal and oblique valleys

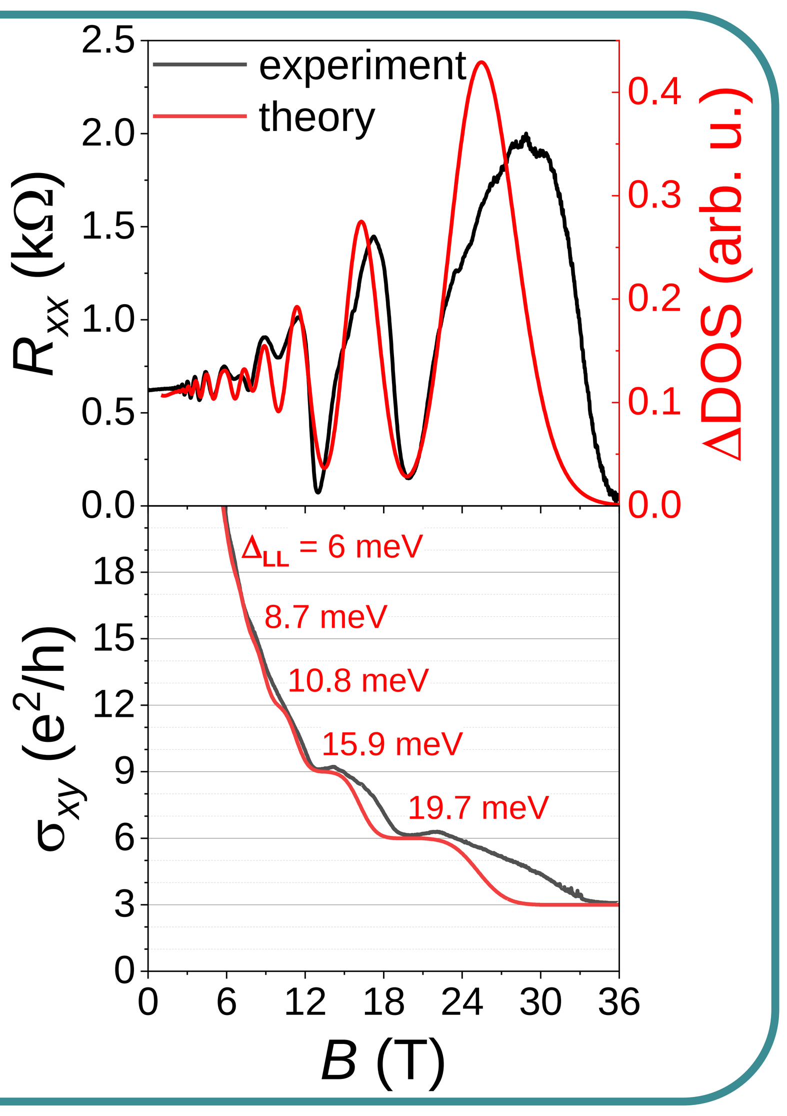
$$\hat{H}\vec{f} = E\vec{f}$$

$$f_n(z) = \sum_j c_n^j \exp\left(i * \frac{2\pi nz}{L_z}\right) / \sqrt{L_z}$$





By adjusting k*p parameters we were able to reproduce SdH oscillations and QHE pattern for a 10 nm QW. However, we were not able to reproduce data for thicker QWs. The Fermi level (-85.3 meV) lies in the valence oblique valley and in the gap of the longitudinal valley. The distance between individual LLs is of the order of 10-30 meV, that's in quantitative agreement with the experimental values for the activation energy and LL broadening.



Acknowledgment

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