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UF

Density Dependence of the Excitation Gap in Si/SiGe Bilayers

Session: Integer Quantum Hall Effect: Transport Phenomena

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3/16/2022

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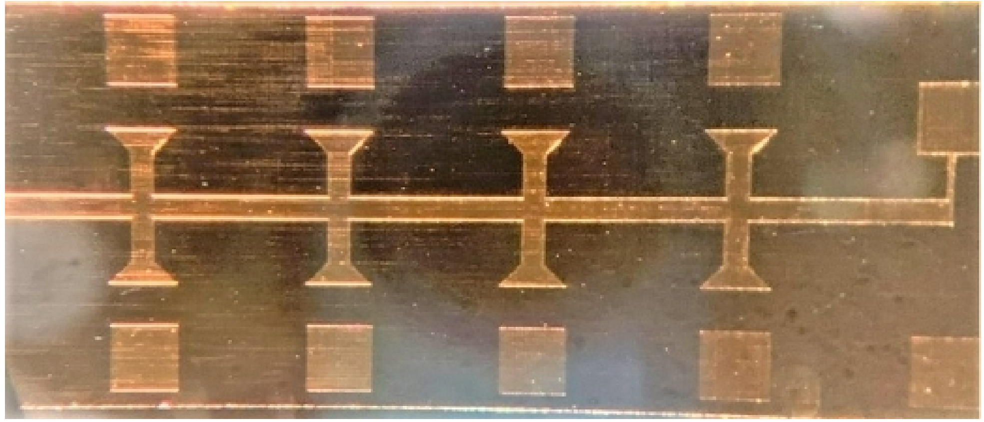
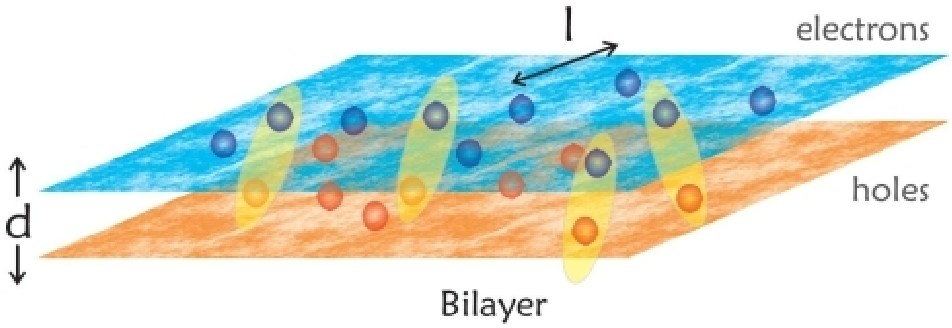
Motivation

- Si-based heterostructures – CMOS technology
- SiGe-based heterostructures
  - Undoped structure with high μ/low disorder
  - ^{28}Si (nuclear spin free) – decoherence
    - Quantum computing
  - Exciton Condensation
    - Resistanceless Transistors
  - Valley Splitting (VS)
    - Valleytronics & Si qubit

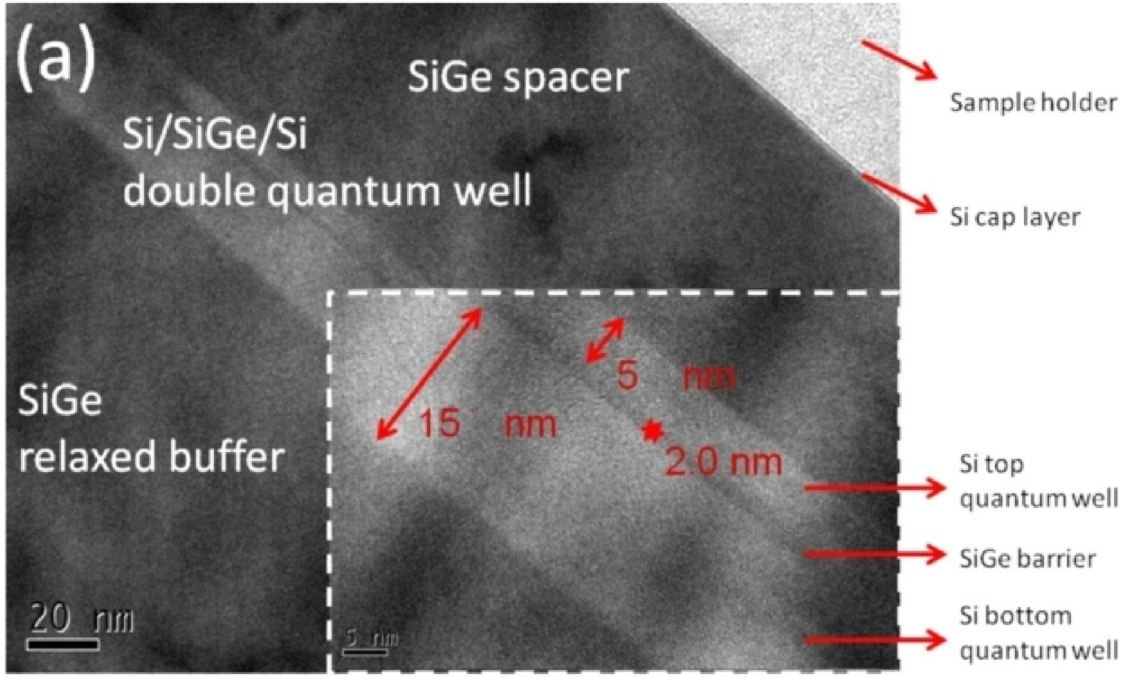


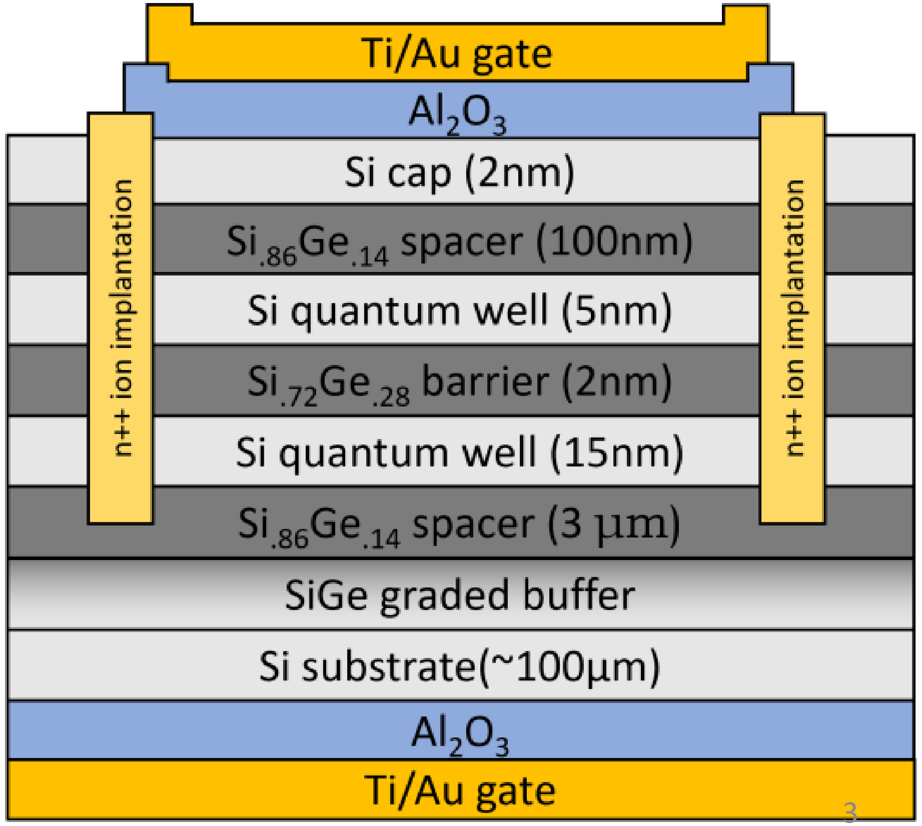


Zefang Wang, Cornell University

Growth & Fabrication

- Undoped & Assymetric Double Quantum Well
- HFET w/ Hall bar geometry patterned using standard fabrication processes
- Front and **BACK** gate capabilities
- Hall densities from 6.8 x 10^{10} cm^{-2} to 3.42 x 10^{11} cm^{-2}
- Hall mobility corresponding to 3.08 x 10^{5} $cm^{2}/(V \cdot s)$

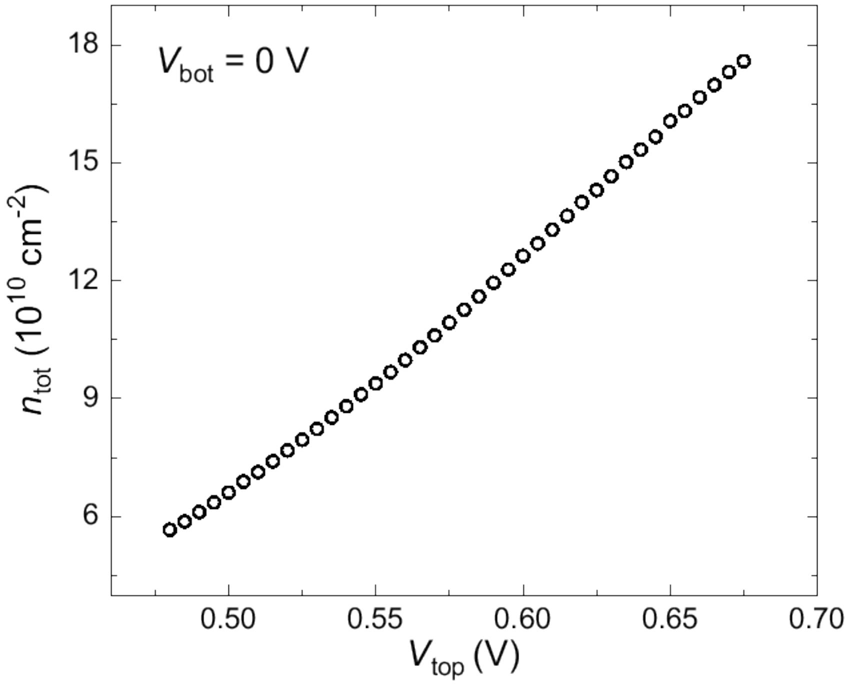


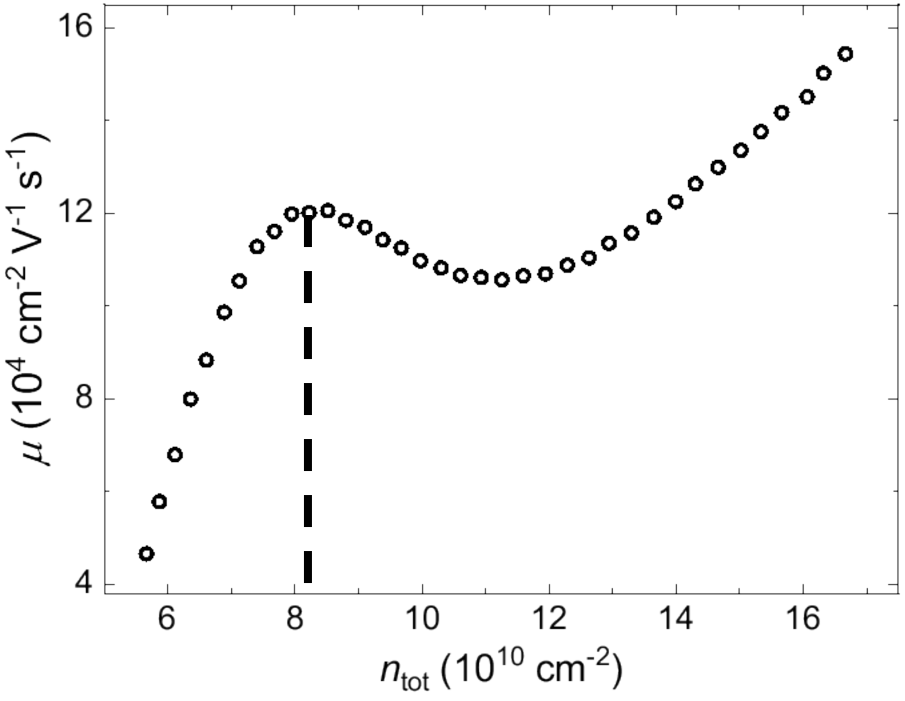


Laroche, Dominique, et al. APL 106.14 (2015)

Bilayer Behavior

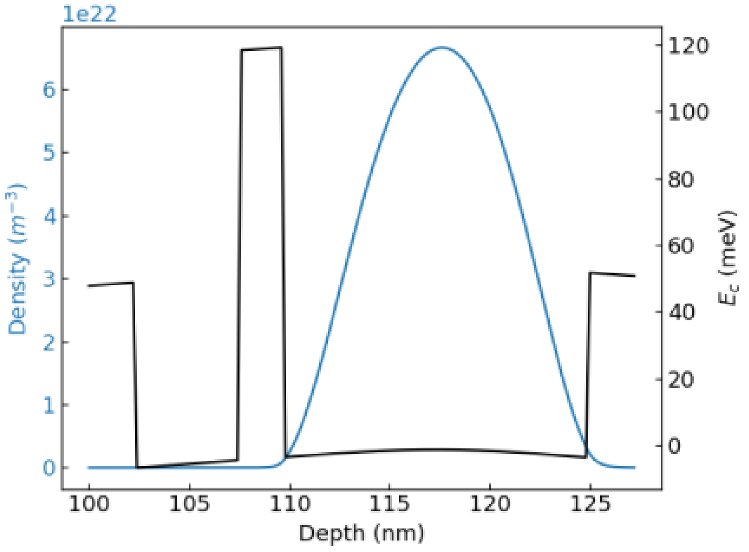
- The mobility increases with Hall density until the crossover density, 8.22 x 10^{10} cm^{-2}. (V_{top} = 0.53 V)
- The mobility then drops to a minimum of 1.06 x 10^5 $cm^2/(V \cdot s)$ due to inter-layer scattering and indicates the bilayer system was formed.





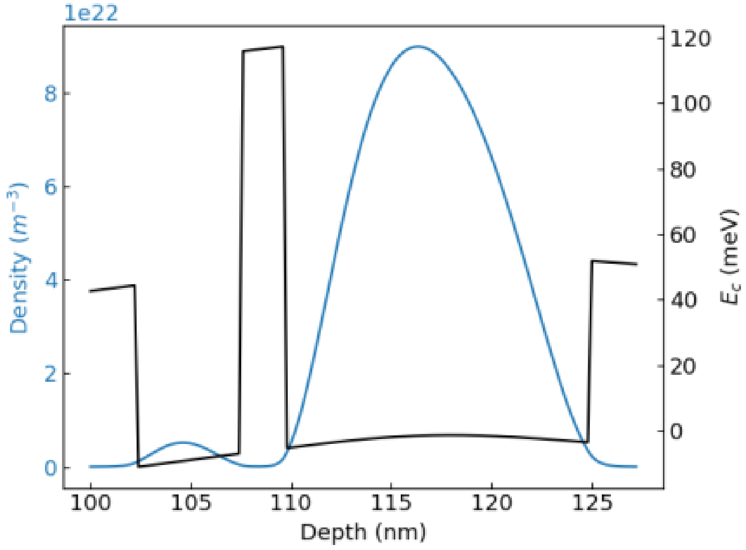
Schrödinger-Poisson Simulations

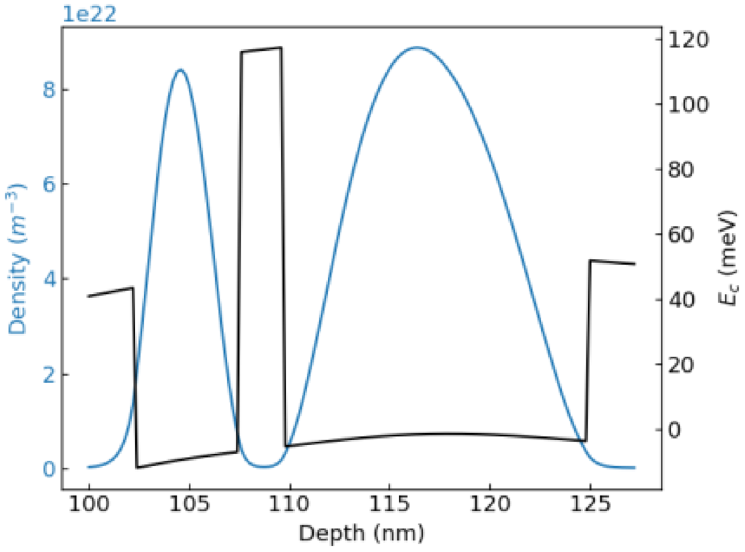
- An iterative, self-consistent SP simulation reproduces $n_{crossover}$ at 8.22×10^{10} cm^{-2}
  - Band gaps were artificially increased at the heterostructure's spacers
  - Nominal growth parameters
- $\Delta_{S,AS} = E_{AS} - E_S$ (Single Electron Tunnel Splitting)



$n_{tot} = 6 \times 10^{10}$ cm^{-2}

$n_{tot} = 8.39 \times 10^{10}$ cm^{-2}

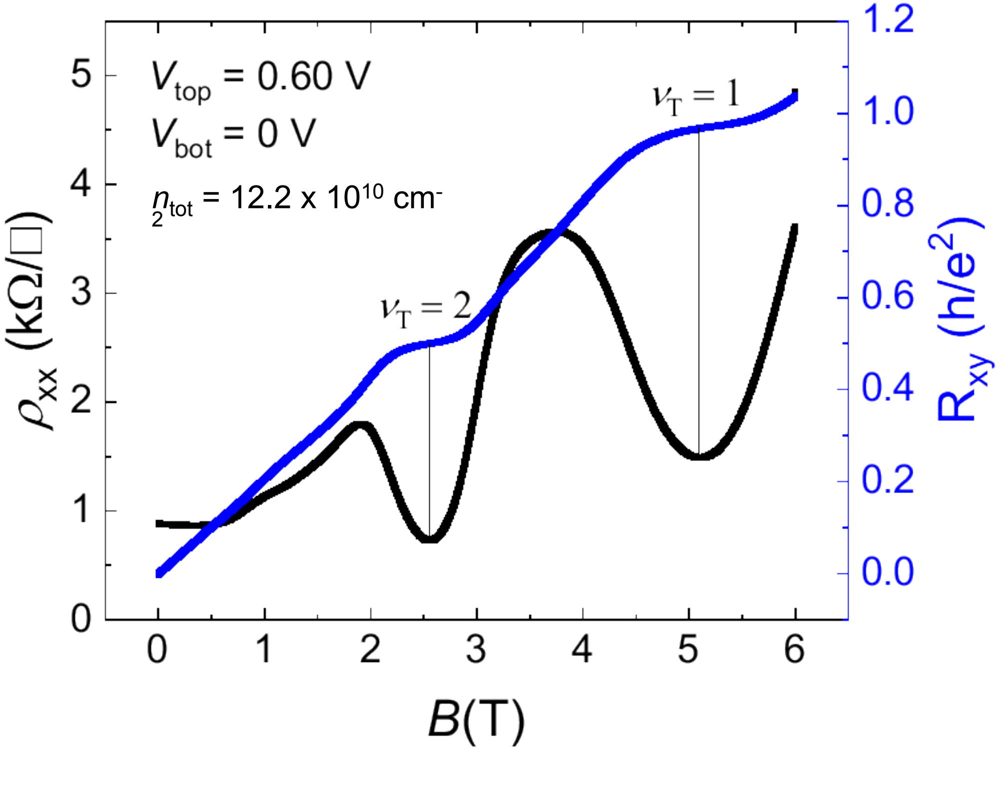


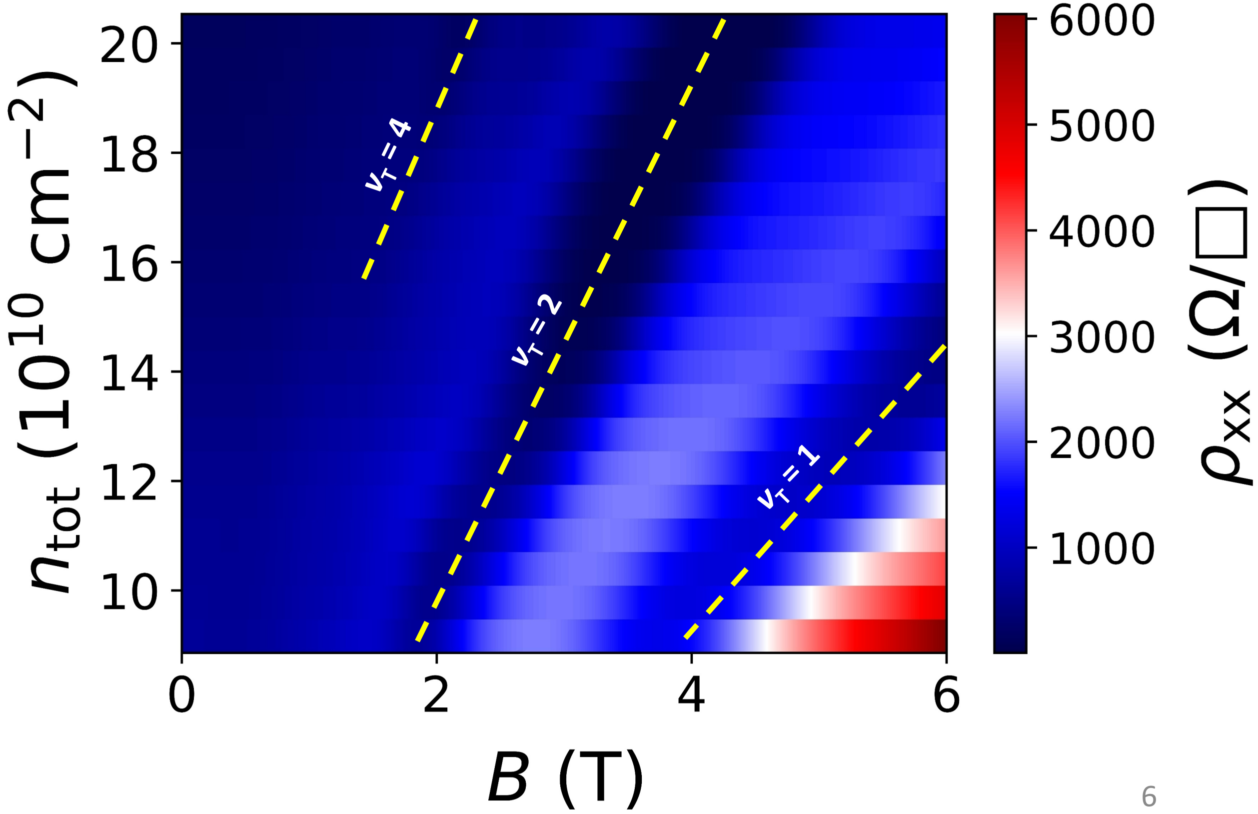


$n_{tot} = 10.9 \times 10^{10}$ cm^{-2}

Front Gate – Variable Imbalanced Densities

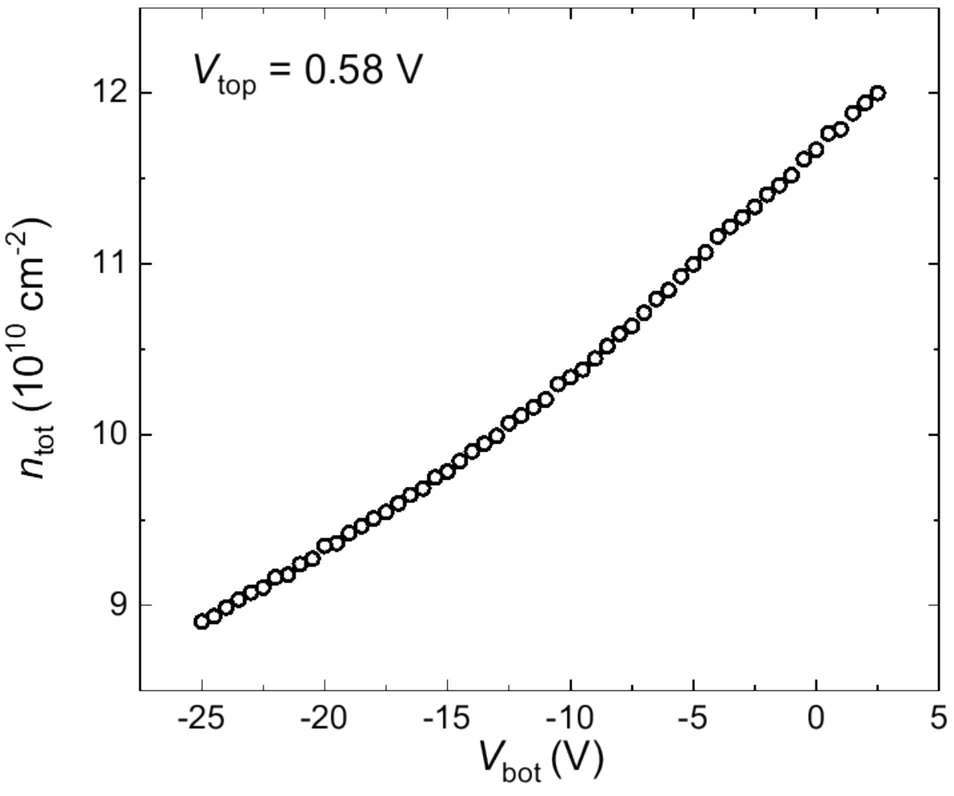
- ν_T = 1,2,4 ρ_{xx} minima evolves with n_{tot} and B
- $R_H = \rho_{xy} = R_K/\nu = h/e^2\nu$

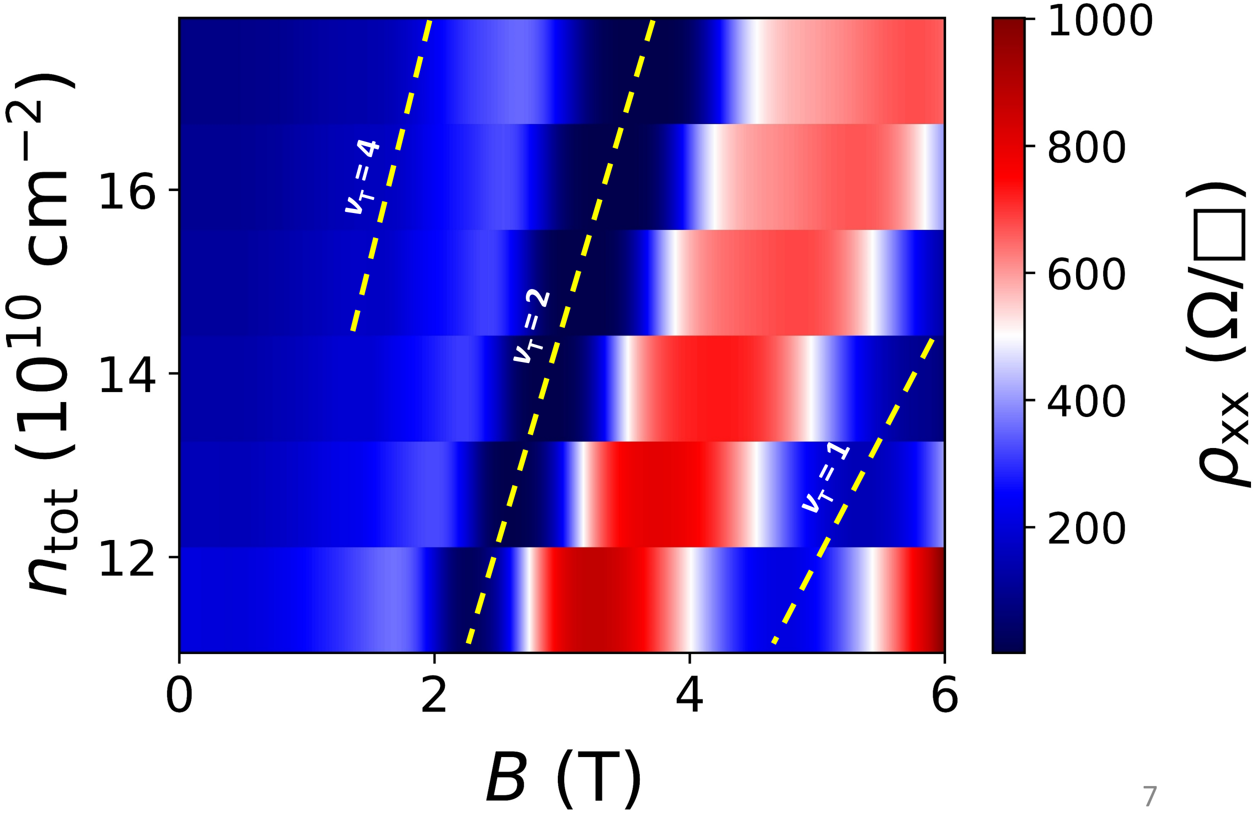




Back Gate - Matched Densities

- Tuned back gate to achieve matched density
- Smaller range of available total densities possible
- ν_T = 1,2,4 ρ_{xx} minima evolves with n_{tot} and B

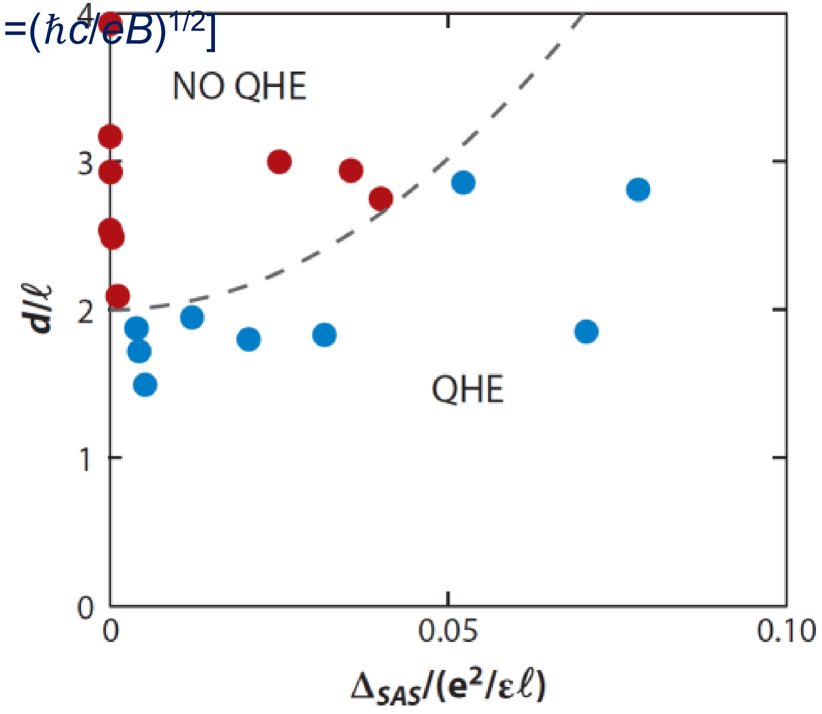




Interlayer Effects

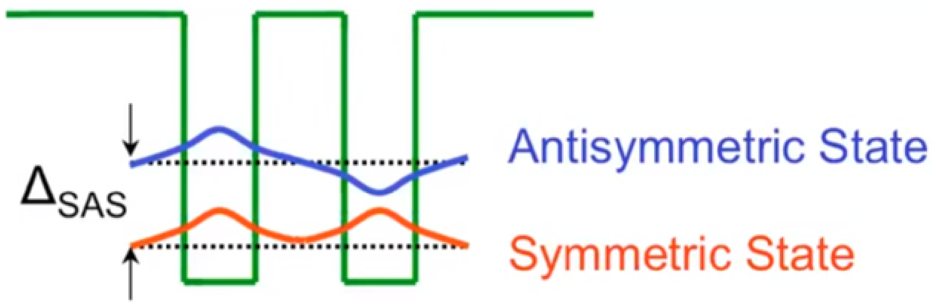
Spontaneous Interlayer Coherence

- Easy-plane ferromagnet or a Bose-Einstein condensate of excitons
- Quantum phase transition to a compressible state above some critical layer spacing, d_c/ℓ_b. [$\ell_b = (\hbar c/eB)^{1/2}$]



Single Particle Tunneling Gap

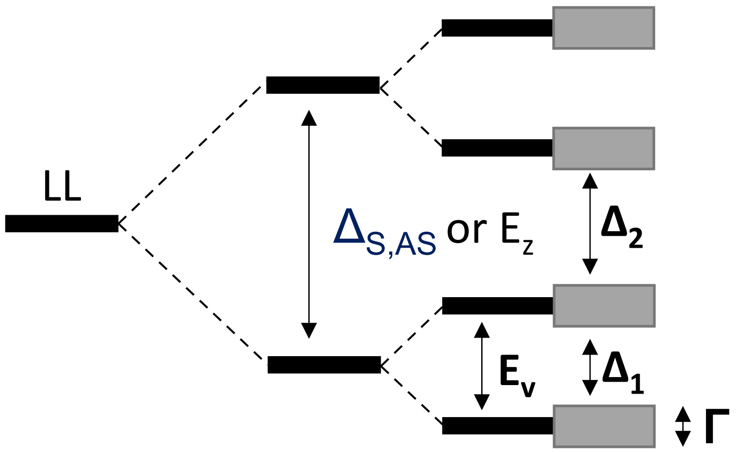
- When tunneling is sufficiently strong, $\Delta_{SAS} = \Delta_{AS} - \Delta_S$
- Δ_{SAS} decreases with increased barrier height and width

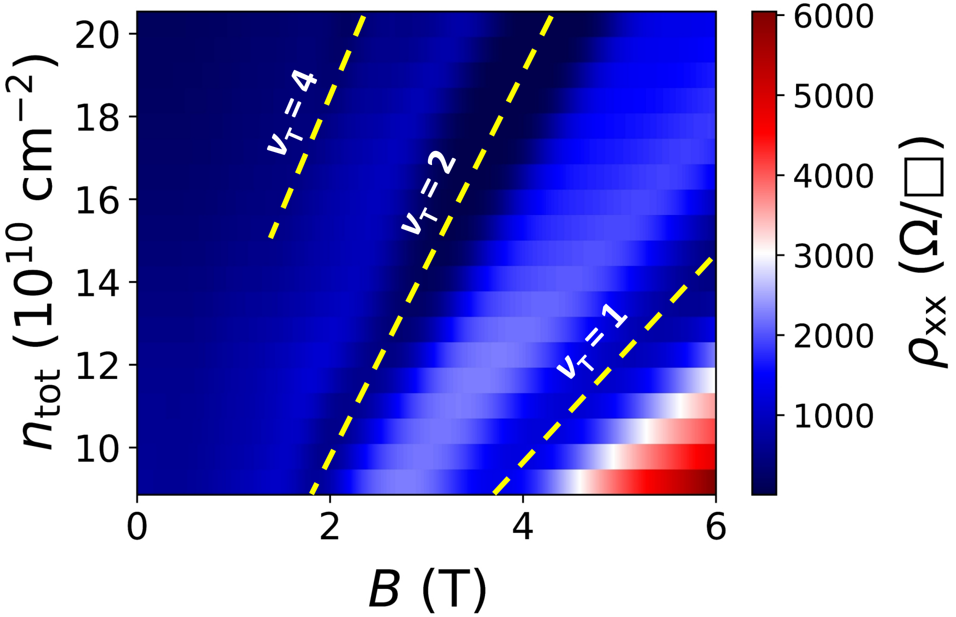


Murphy SQ, et al. Phys. Rev. Lett. 72:728–31 (1994)

Degeneracies

- **Single layer regime**: spins (↑↓) and valleys (+/-)
  - Valley splitting and spin is linear with $n_{tot}(B)$
  - @ 4.13 T, $E_v \approx 1.35$ K < $E_z \approx 2.79$ K → $\nu_T = 1$ ($\nu_T = 2$) attributed to valley (spin)
- **Bilayer regime**: layer (S/AS) degree of freedom
  - Single particle tunneling gap, Δ_{SAS} , can be estimated from SP
  - No LL crossing when transitioning into the bilayer state
    - $\nu_T = 1$ is attributed to valley
    - $\nu_T = 2$ is attributed to interlayer effects

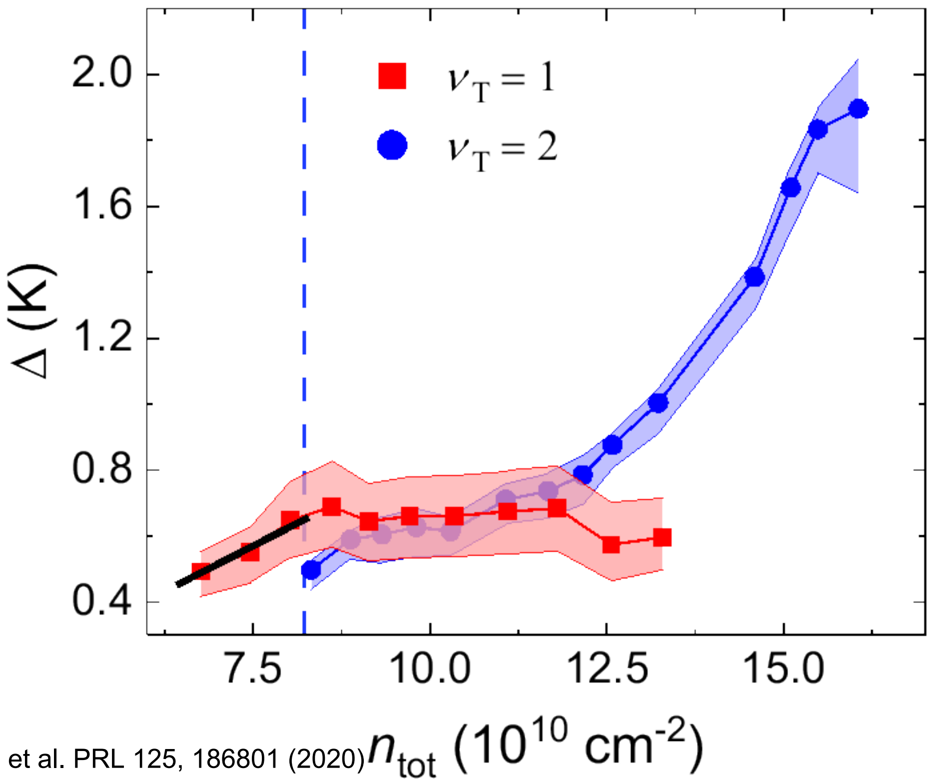




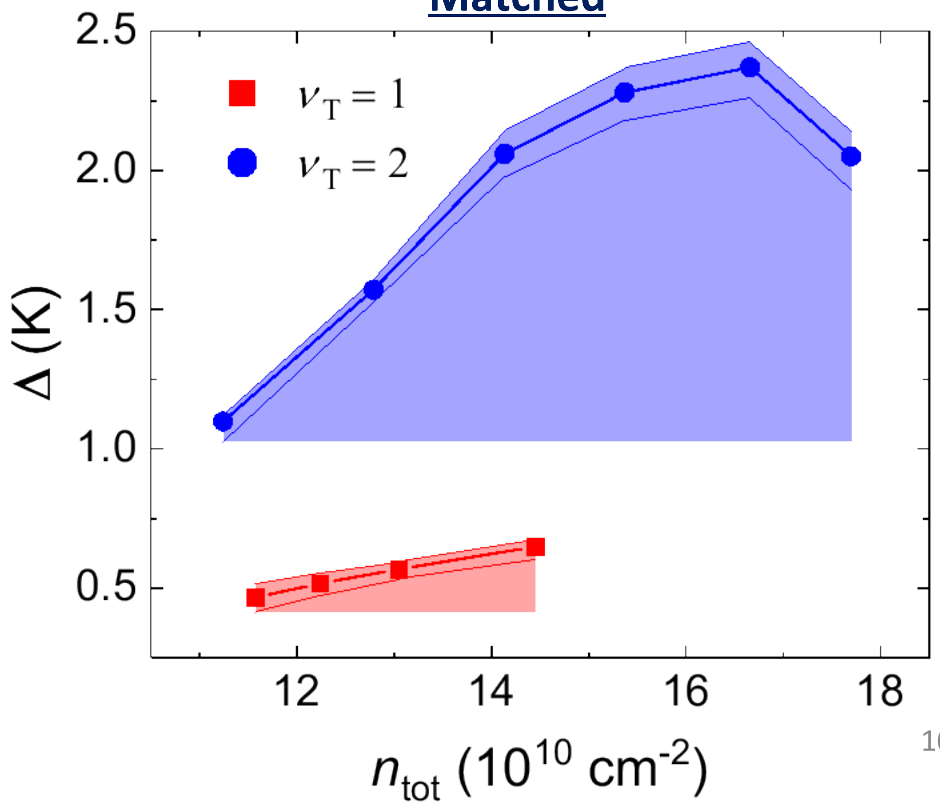
Extracted Activation Gaps

- The activation gaps were extracted through temperature dependence scans
- Non-linear behavior for both $\nu_T = 1$ and $\nu_T = 2$ at variable imbalanced and matched densities
- Valley [1], spin and Landau gaps should evolve linearly to 1st order w/ B in the absence of subband crossing

Variable imbalanced



Matched



[1] B.P. Wuetz et al. PRL 125, 186801 (2020)

E_{2n} Results

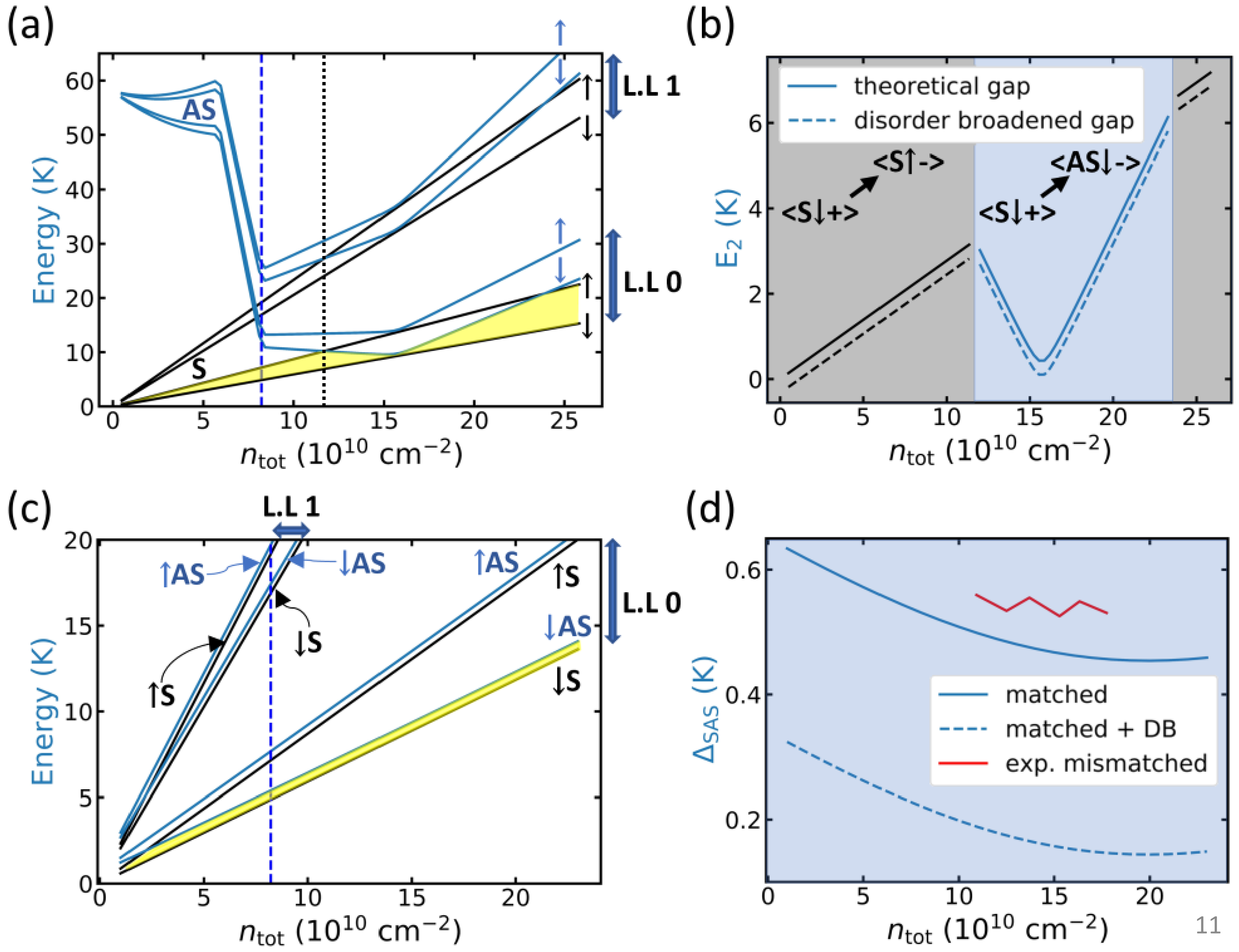
Fan diagram generated by SP simulation: 4 energy sub-levels per LL since VS omitted

Variable Imbalanced Densities:

E_z and Δ_{SAS}

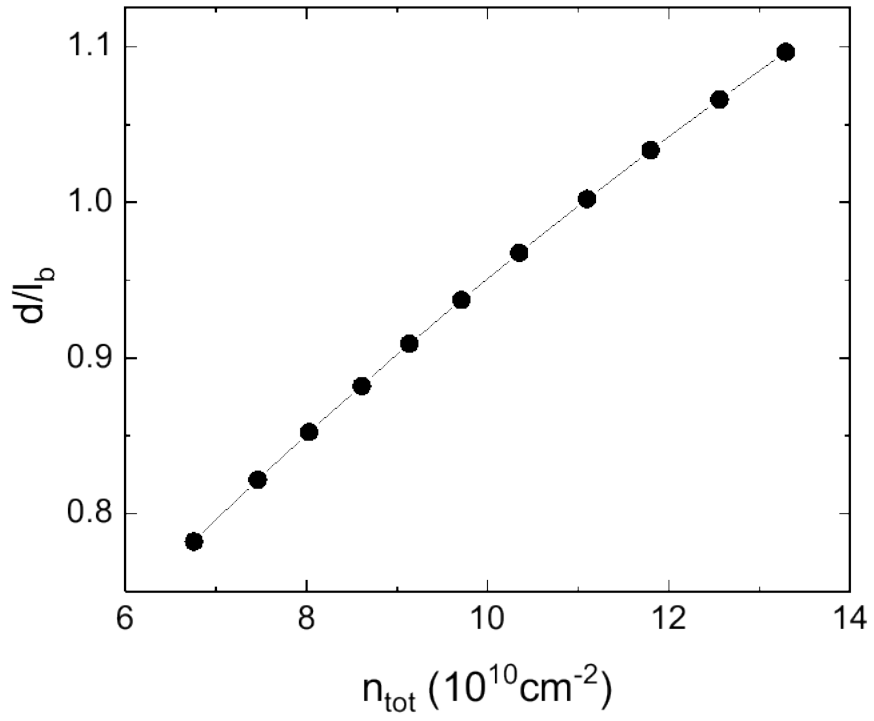
Matched Densities:

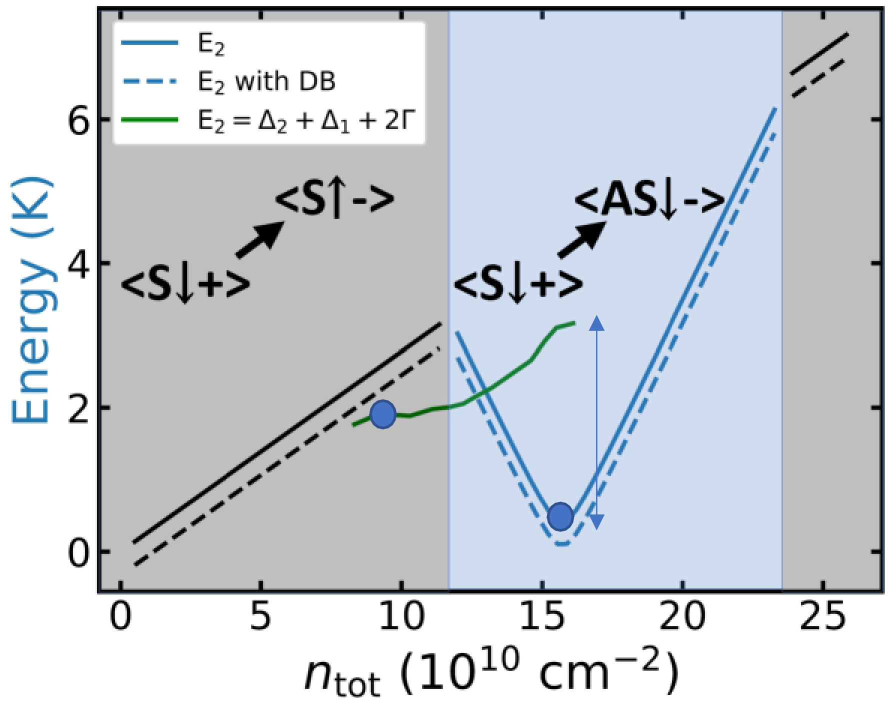
Δ_{SAS}



Interpreting ν_T = 2

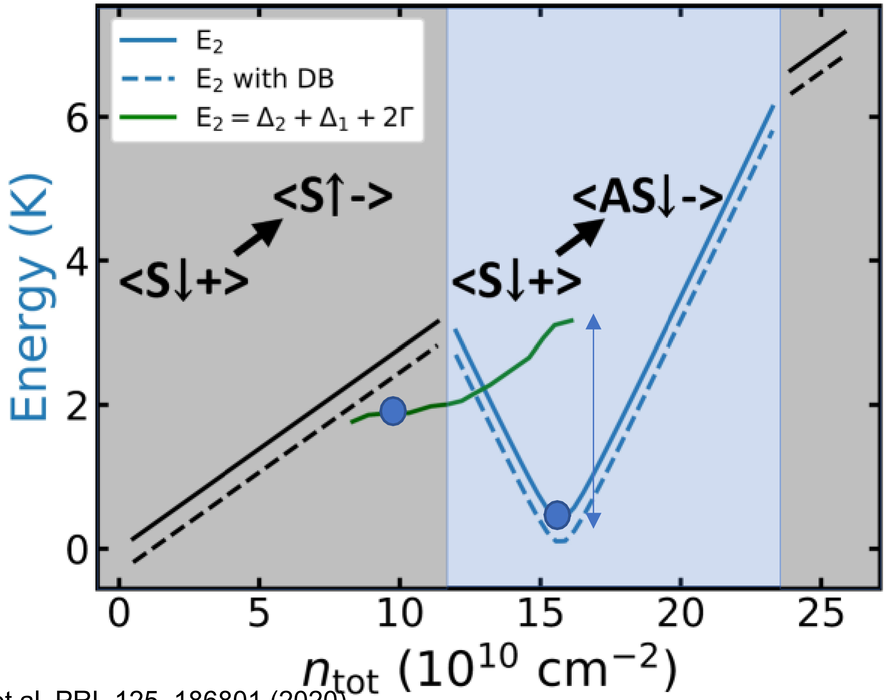
- Interplay between spin splitting and interlayer effects, Δ_{SAS} & SIC
- **Device**: d/ℓ_b = [0.62-1.24] & $e^2/\varepsilon\ell_b \approx 5 \times 10^{-4}$ indicating SIC is possible
- From theory, $\Delta_2 = E_2 - E_1 - \Gamma = E_2 - \Delta_1 - 2\Gamma$
- Δ_1 unknown at low n(B)

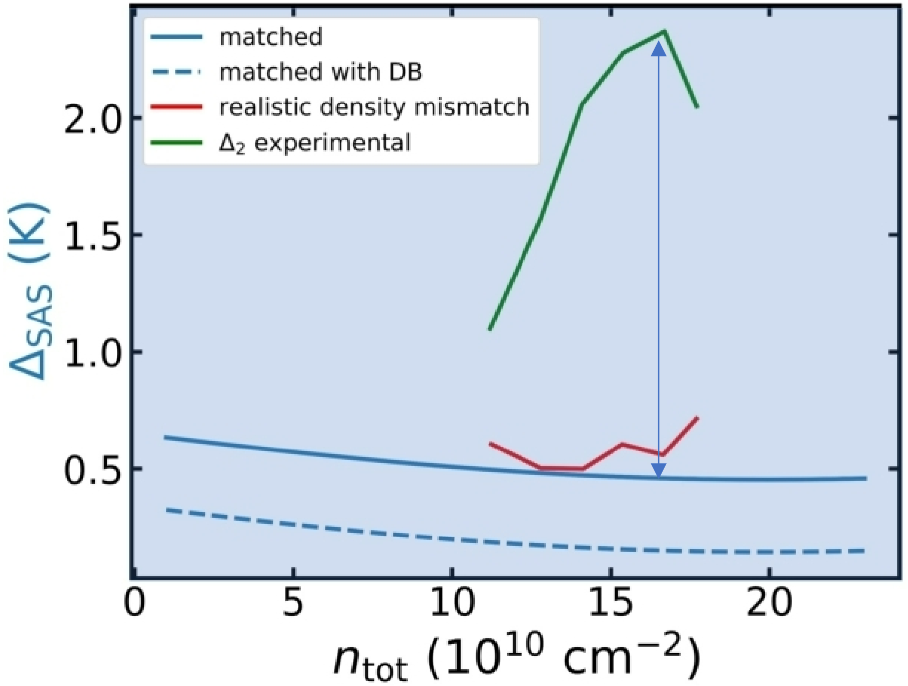




Interpreting $\nu_T = 2$

- Neither Δ_{SAS}, spin splitting, nor LL spacing alone reproduces Δ_2.
- Strength of Δ_2 ↑, induced by SIC:
  - d/ℓ_b ↓
  - $\Delta\nu$ ↑
  - **Δ_{SAS}** ↓



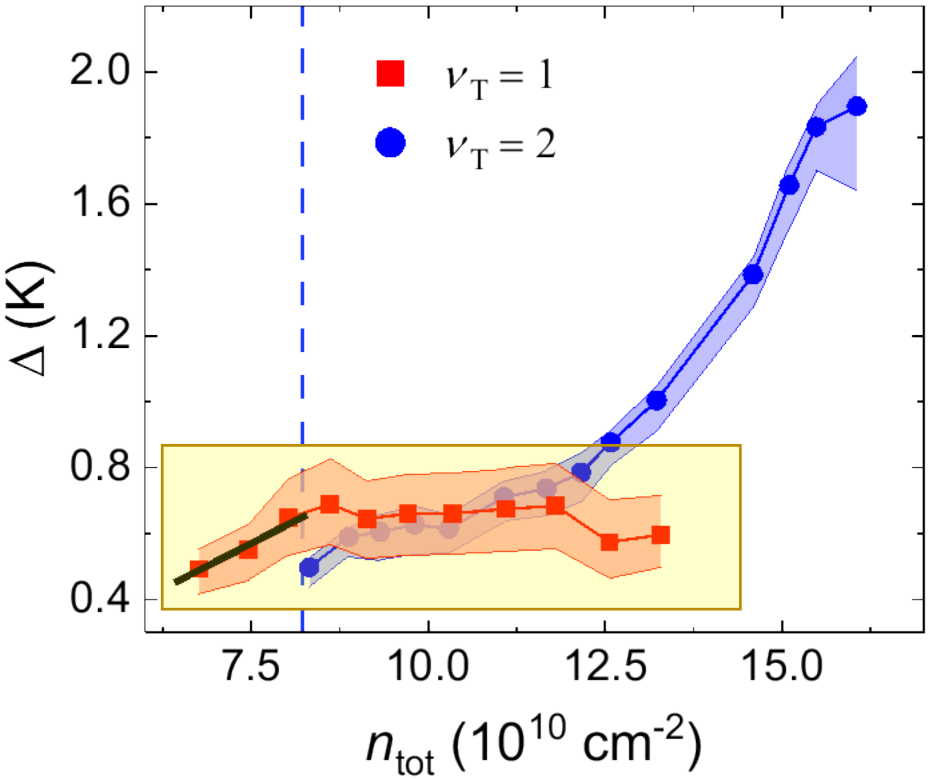


[1] B.P. Wuetz et al. PRL 125, 186801 (2020)

Valley Splitting & $\nu_T = 1$

- **Single Layer**: Disorder broadening, $\Gamma \approx 0.327$ K and linear coefficient, $c_B \approx 0.29$ K/T
  - $\Delta_v = E_v - \Gamma = c_B B - \Gamma$
- The bilayer dependence decreases and nearly flattens out (not understood)
- Si may exhibit large valley splitting at low B or spontaneous valley polarization

Variable Imbalanced



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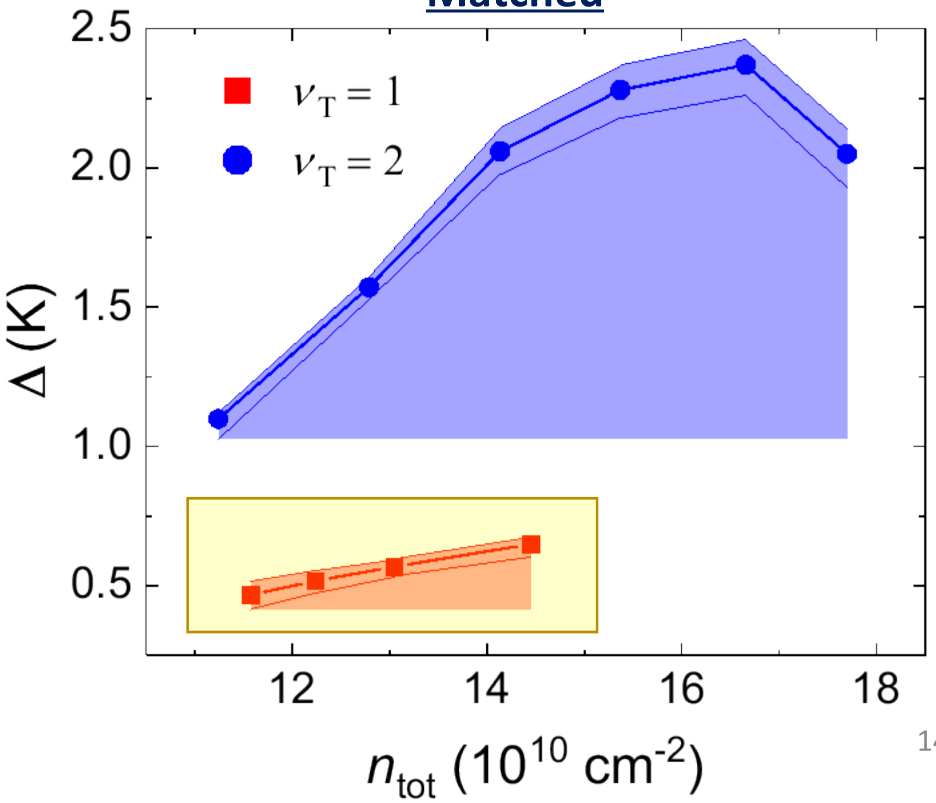

Thank you for your attention!

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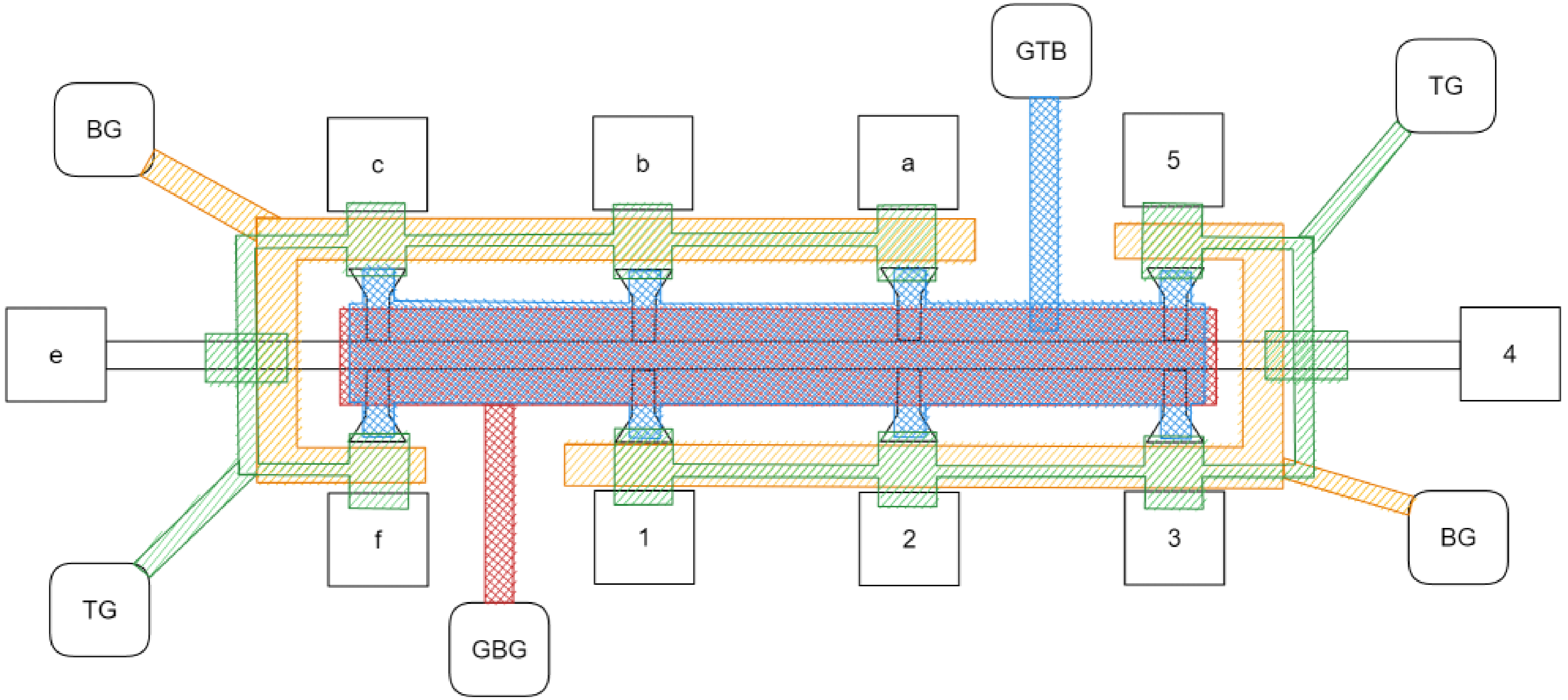
Summary

Dual gated undoped Si/SiGe bilayer

Single & Bilayer quantum Hall states at ν_T = 1,2

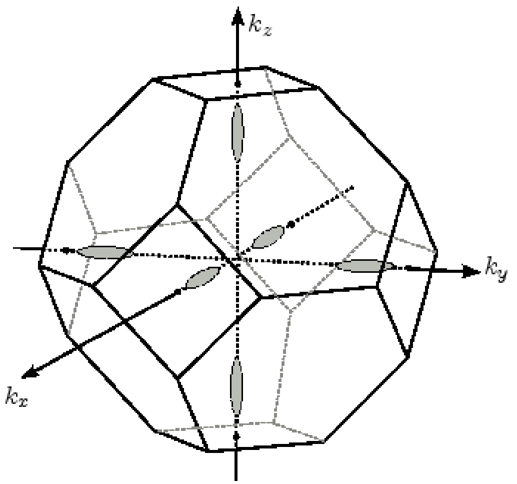
Evidence of Exciton Condensation warrants further investigation

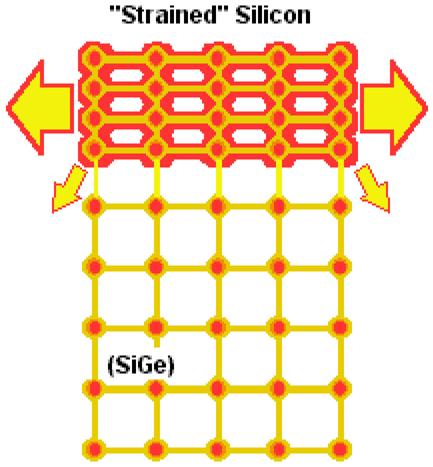


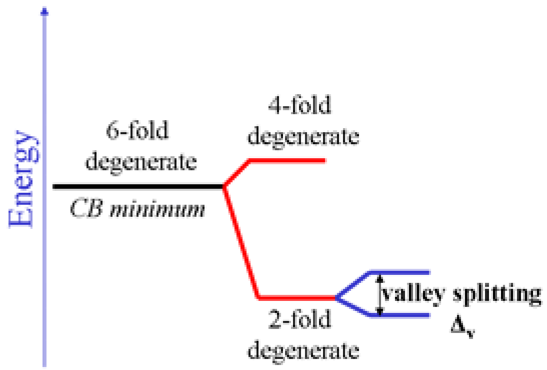
Questions?

Valley Splitting in Single Layers

- In bulk Si, there is a 6-fold valley degeneracy
  - Tensile strain reduces it to 2-fold
  - Quantum confinement from the sharp quantum well interface lifts the degeneracy
- Atomic-scale disorder suppresses valley splitting
- Large valley splitting may be important for quantum computing



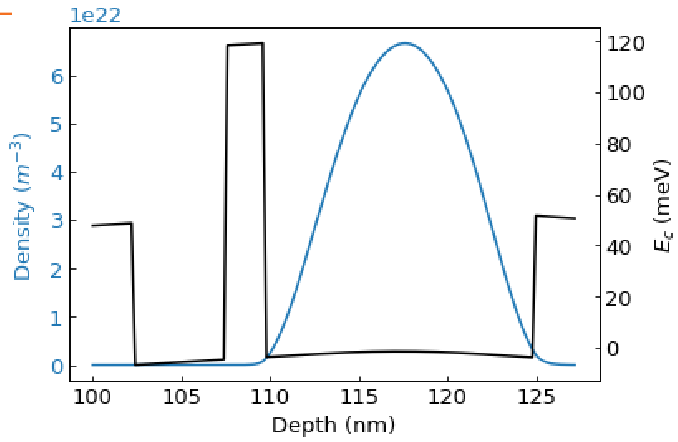




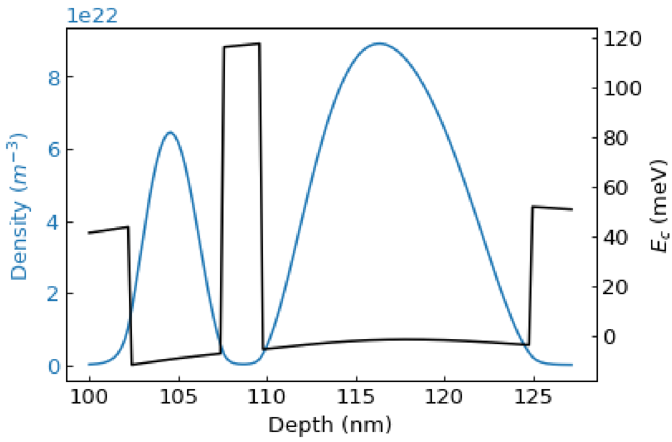
Achieving Matched Density

1. As V_{top} increased, n_{bot} increases until it saturates at $n_{crossover}$
2. n_{bot} stays constant past $n_{crossover}$ due to top layer screening
3. Now change V_{bot} (n^0_{top} unaffected by V_{bot} due to bottom layer screening)
   - $n^0_{top} = n_{tot} – n_{crossover}$
4. Thus, $n_{bot} = n_{tot} – n^0_{top}$

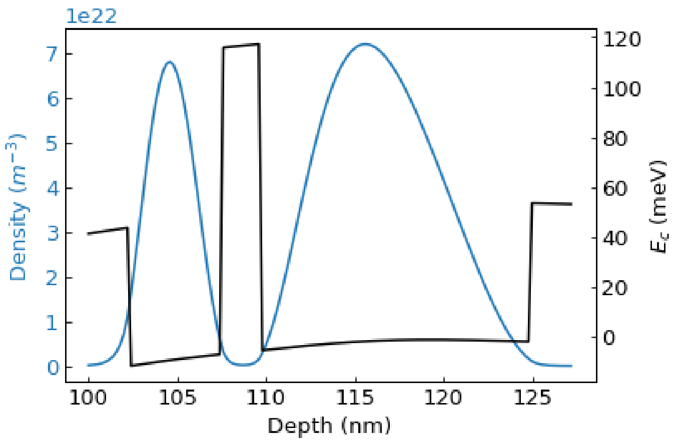
Matched density is achieved by collating the density dependence on the gates.



n_{top} = 2 x 10^6 cm^{-2}
n_{bot} = 6 x 10^{10} cm^{-2}



n_{top} = *2.1 x 10^{10} cm^{-2}*
n_{bot} = 8.22 x 10^{10} cm^{-2}



n_{top} = *2.2 x 10^{10} cm^{-2}*
n_{bot} = 6.12 x 10^{10} cm^{-2}

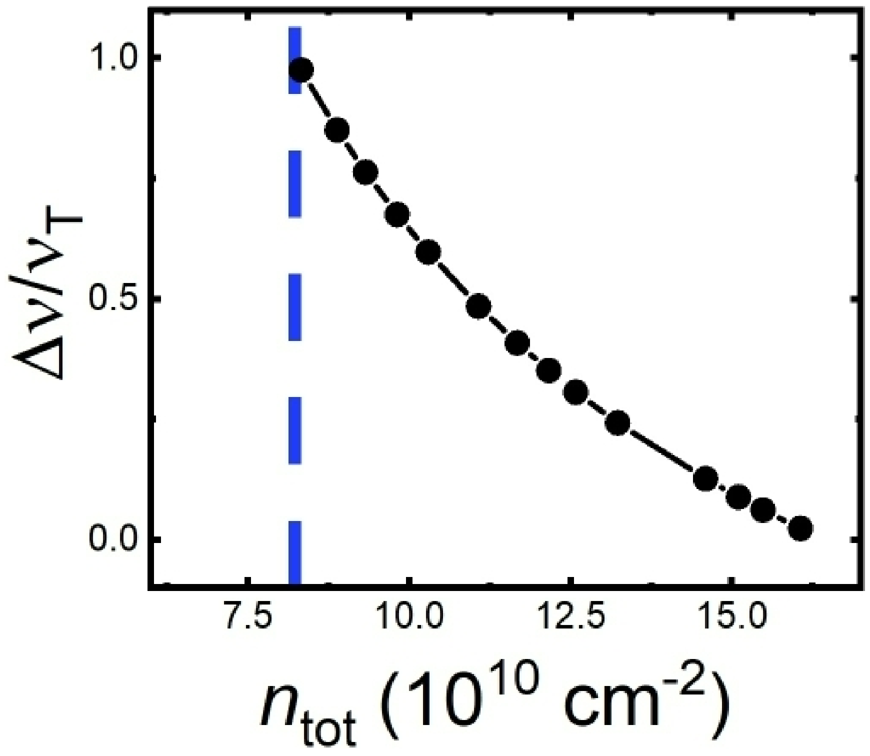
Achieving Matched Density

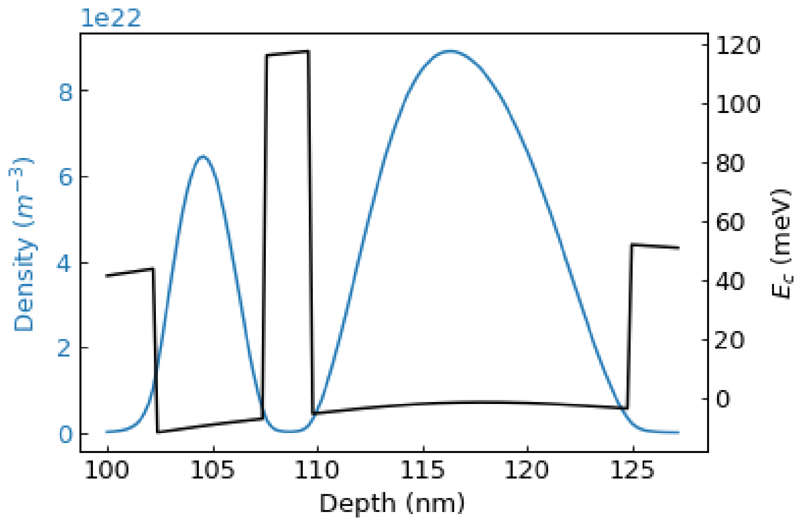
- As V_{top} increased, n_{bot} increases until it saturates at $n_{crossover}$
- n_{bot} stays constant past $n_{crossover}$ due to top layer screening (change V_{bot})
- $n^0_{top} = n_{tot} - n_{crossover}$ (n^0_{top} unaffected by V_{bot} due to bottom layer screening)
- Thus, $n_{bot} = n_{tot} - n^0_{top}$
- Matched density is achieved by collating the density dependence on the gates.

V_{top} (V)	V_{bot} (V)	n_{tot} (10^{10} cm^{-2})	n_{top} (10^{10} cm^{-2})	n_{bot} (10^{10} cm^{-2})	% Difference
0.62	-26.525	11.24	5.77	5.47	5.47
0.63	-18.976	12.79	6.43	6.36	1.22
0.64	-12.368	14.14	7.11	7.03	1.18
0.65	-6.375	15.37	7.84	7.53	4.04
0.66	-1.375	16.66	8.44	8.22	2.74
0.67	3.457	17.7	9.09	8.61	5.5
0.62*	-26.525*	11.57	5.77	5.8	0.53
0.625*	-22.613*	12.24	6.08	6.16	1.33
0.63*	-18.976*	13.05	6.43	6.62	2.76
0.64*	-12.368*	14.45	7.11	7.34	3.16

Density Imbalance

- $\nu_T = n_T/(eB/h)$ & $\Delta\nu = \nu_1 - \nu_2$
- $\Delta\nu/\nu_T = (\nu_1-\nu_2)/2 \approx 0.5$ @ $n_{tot} = 11.07 \times 10^{10}$ cm^{-2}
- The onset of Δ_2's magnitude increase coincides w/ $\Delta\nu/\nu_T \approx 0.5$

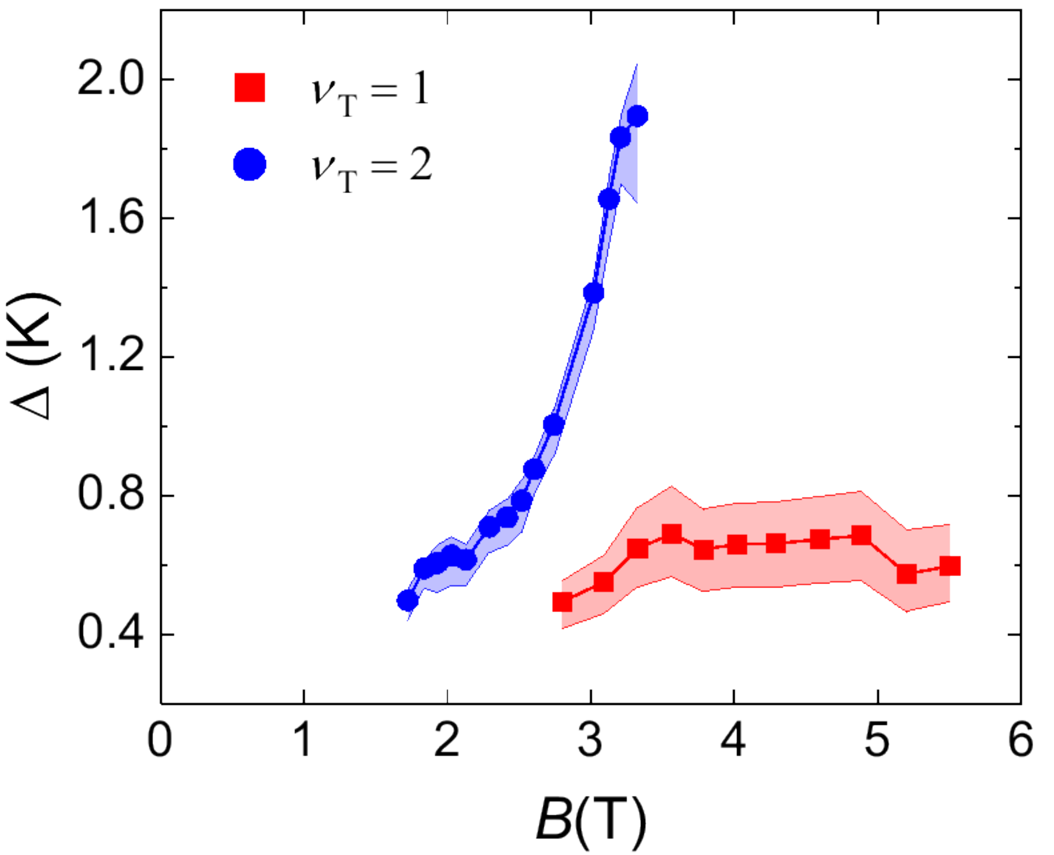




Δ vs B

- $R_H = \rho_{xy} = R_K/\nu = h/e^2\nu$ (1980) $[\nu_T = n_T/(eB/h)]$

Variable Imbalanced



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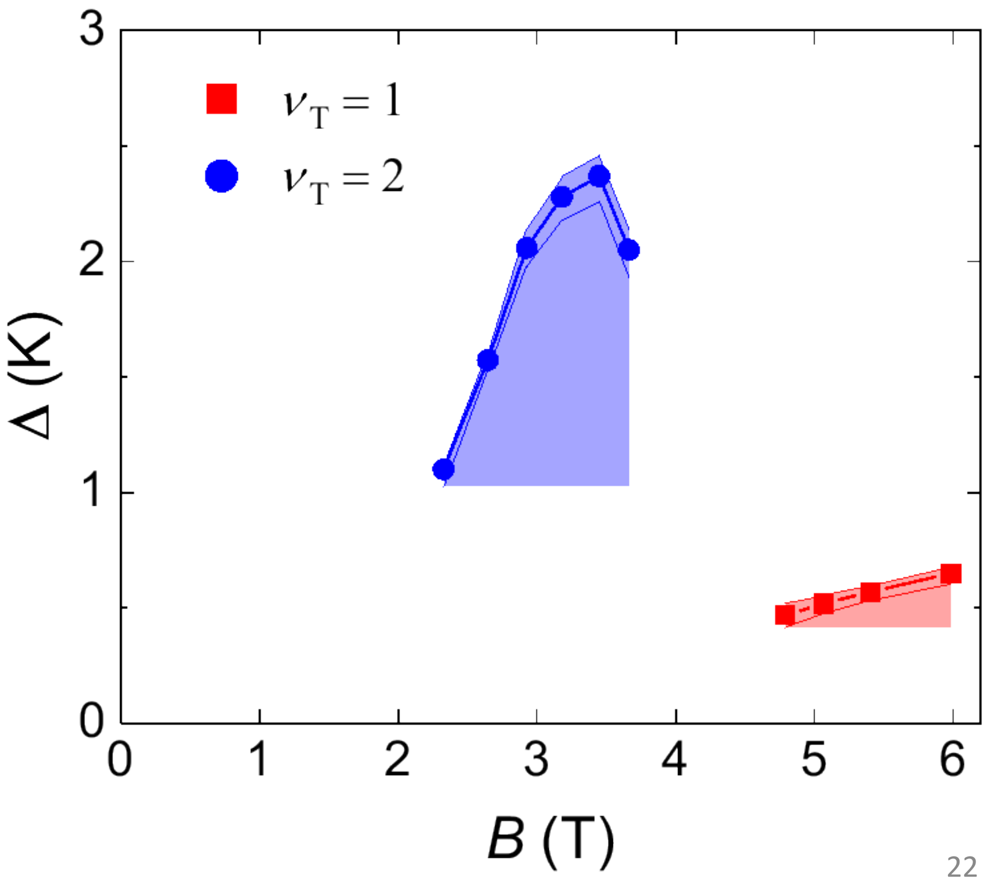
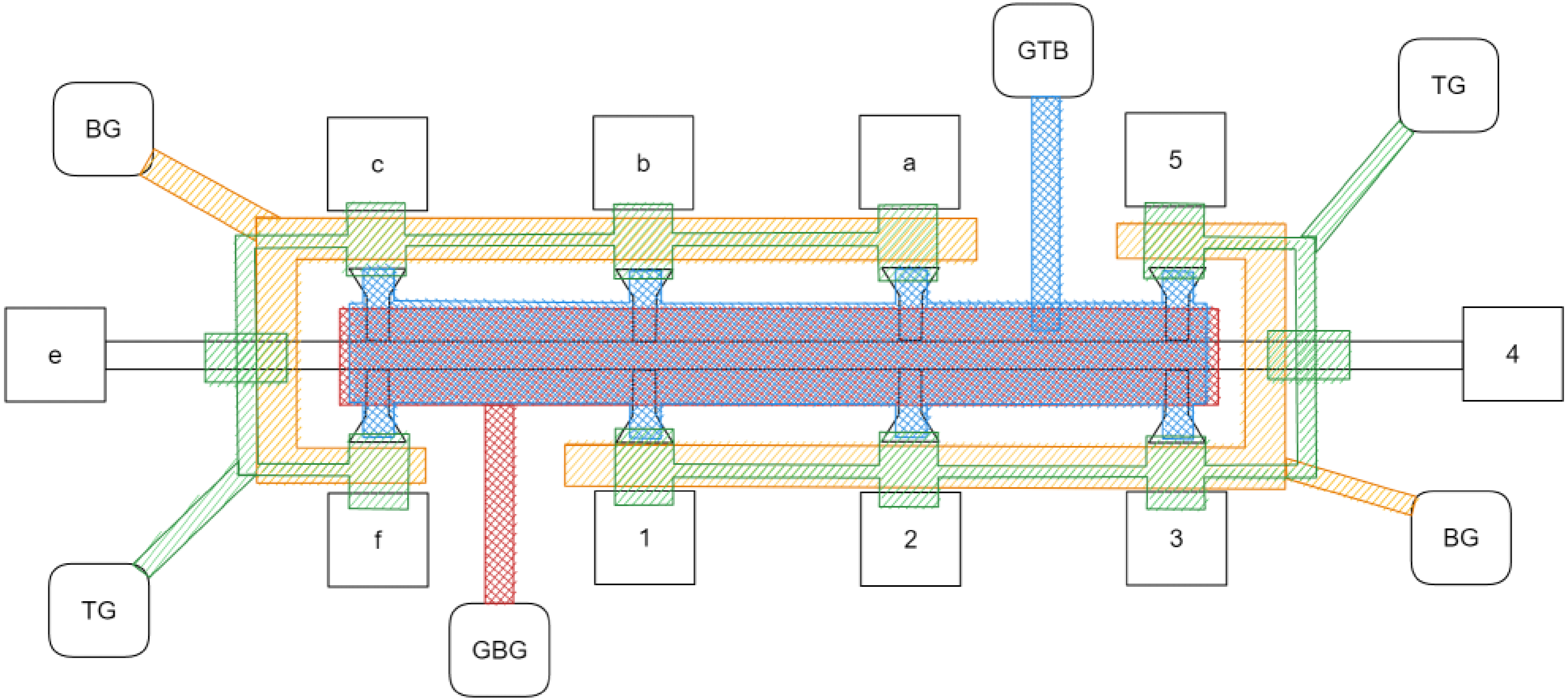


FUTURE WORK

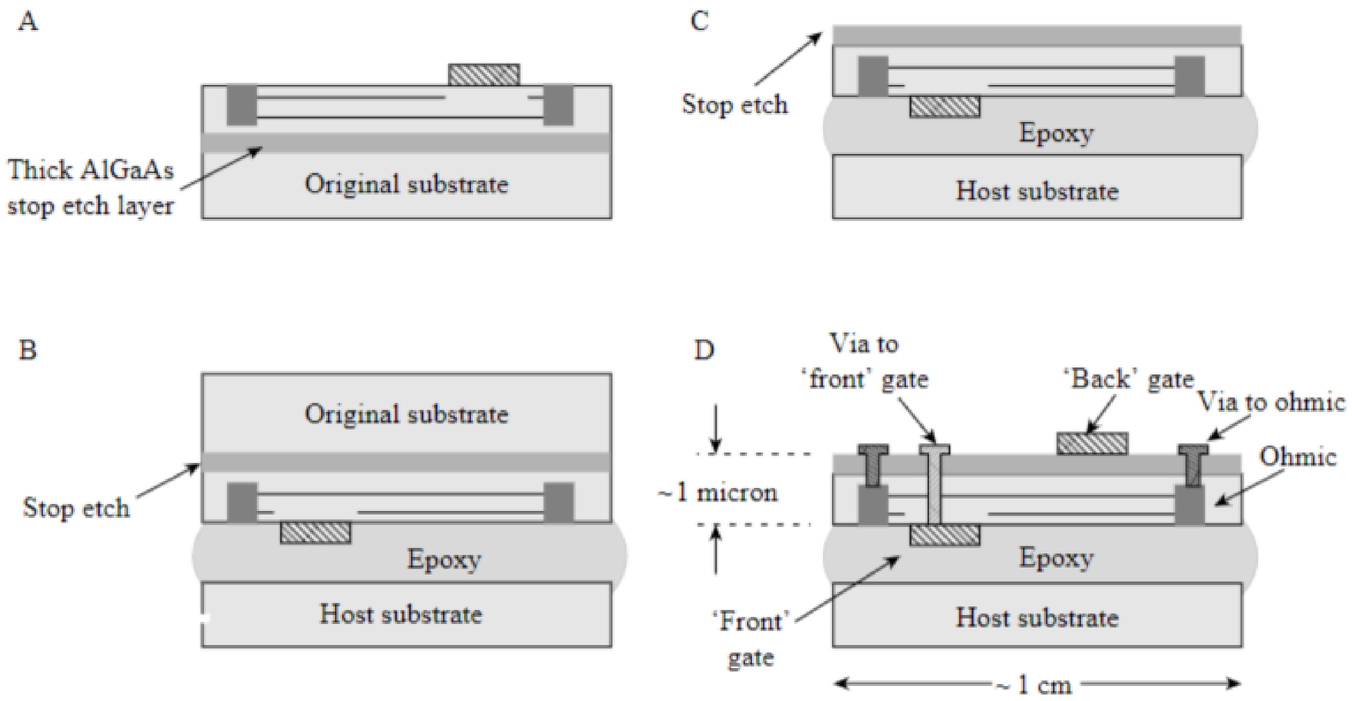
Independent Contacts

- Designing a scheme to independently contact both layers simultaneously
- A combination of top/bottom accumulation gates + density gates
  - Global Top (Bot) Gate: Blue (Red)   Contact Top (Bot) Gate: Green (Yellow)
- Unlocks tunneling conductance, Coulomb drag, and counterflow measurements



NRF Fabrication

- Measuring Si/SiGe devices over a larger density range
  - Reduce the distance between the bottom QW and the bottom gate
  - Utilizing larger magnetic fields
- Fabricating Ge/SiGe bilayer devices at NRF
  - EBASE[1] technique (Tetramethylammonium hydroxide (TMAH))
  - Valley splitting dependence using a tilted magnetic field



[1] Weckwerth, M. V., et al. Superlattices and Microstruct. 20.4 (1996)