Electron bilayers in an undoped Si/SiGe double-quantum-well heterostructure

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Motivation

Electron bilayers :

- Electron bilayers in GaAs exhibit novel phenomena arising from inter-layer correlation: even denominator fractional quantum Hall states and BEC of excitons.
- Bilayer quantum Hall states potentially can be used for quantum computing.

Electron bilayers in Si/SiGe :

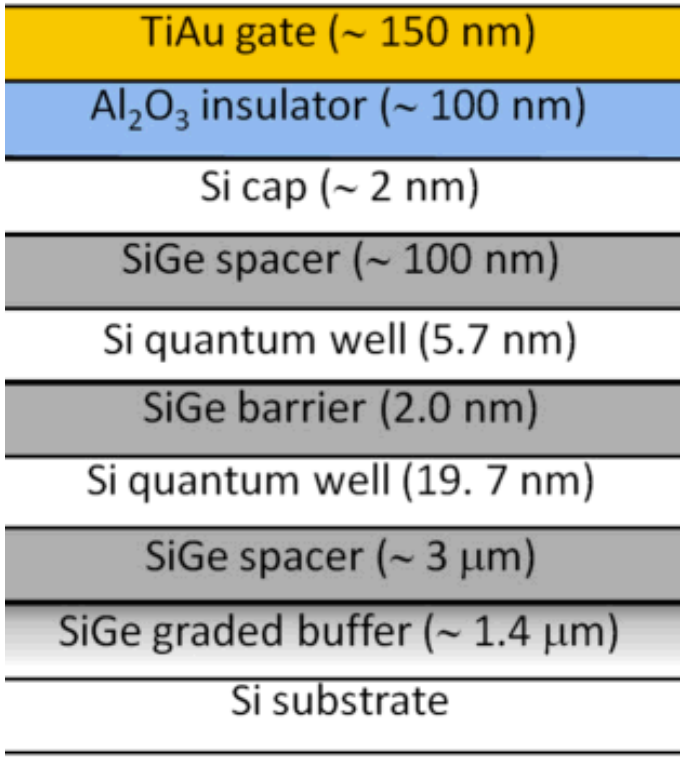
- To obtain an electron bilayer in a Si/SiGe heterostructure using the conventional modulation-doping technique, doping needs to be done before the lower quantum well is grown to provide electrons to the lower well.
- Surface segregation of donors means that donors ride on top of the growth front and compromise the quality of the 2D electron system.

Our approach to create electron bilayers in Si/SiGe:

- Undoped Si/SiGe heterostructures
- Electrons are accumulated in the quantum wells by gating
- A carefully designed stack to allow simultaneous occupation of two wells at measurable densities.

Heterostructure design

Ge = 14 %



Design considerations for undoped, front-side-gated devices:

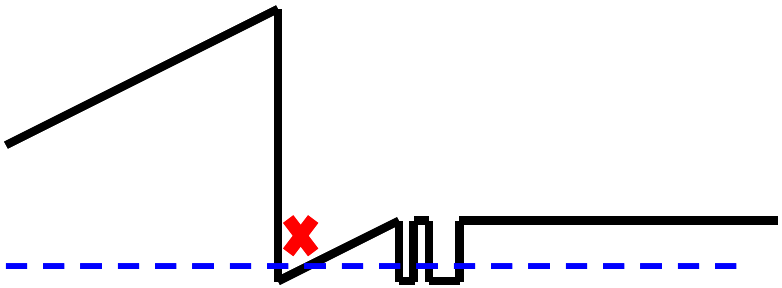
1. Front-side gating means that the top quantum well screens the bottom quantum well.
2. The top quantum well needs to be thin to push the ground state energy high. The bottom quantum well is then filled first until the Fermi energy crosses the ground state energy of the top quantum well.
3. The interlayer SiGe barrier needs to be thin so that the voltage drop across the barrier is small, and there is a measurable density in the bottom quantum well when the crossing occurs.
4. The thin SiGe barrier layer also enhances the interlayer Coulomb energy.

Self-consistent SP simulations

We performed 1-dimensional Schrodinger-Poisson calculations to estimate the electron density in the upper and lower wells of our bilayer structure.

- **Algorithm**:
  - Start with material (layer) information -> starting **potential**
  - Solve Schrodinger equation using **potential** -> **states**
  - Solve non-linear Poisson equation using predictor-corrector density functional of **states**.
  - Repeat until converged.

- **Important note**: because SiGe devices are known to operate out of equilibrium, we *artificially do not permit accumulation* of electrons at the oxide interface.



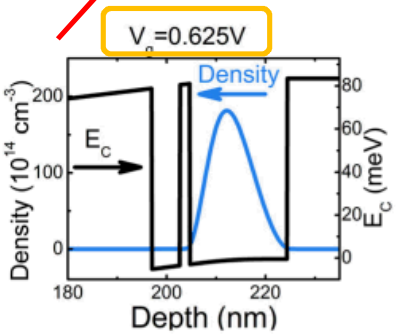
Heterostructure design

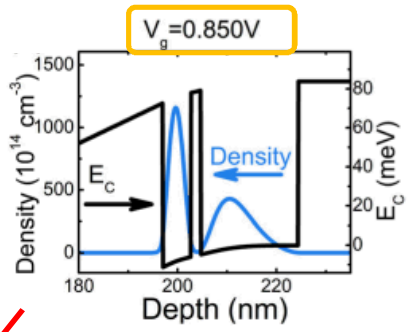
Ge = 14 %

Target thicknesses

TiAu gate (~ 150 nm)	
Al_2O_3 insulator (~ 100 nm)	100 nm
Si cap (~ 2 nm)	5 nm
SiGe spacer (~ 100 nm)	2nm
Si quantum well (5.7 nm)	15 nm
SiGe barrier (2.0 nm)	
Si quantum well (19. 7 nm)	
SiGe spacer (~ 3 µm)	
SiGe graded buffer (~ 1.4 µm)	
Si substrate	

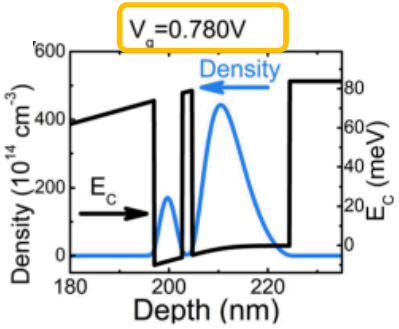
Accumulation in bottom layer





Accumulation in top layer

4 x 10^{10} cm^{-2} measurable



Onset of accumulation in top layer

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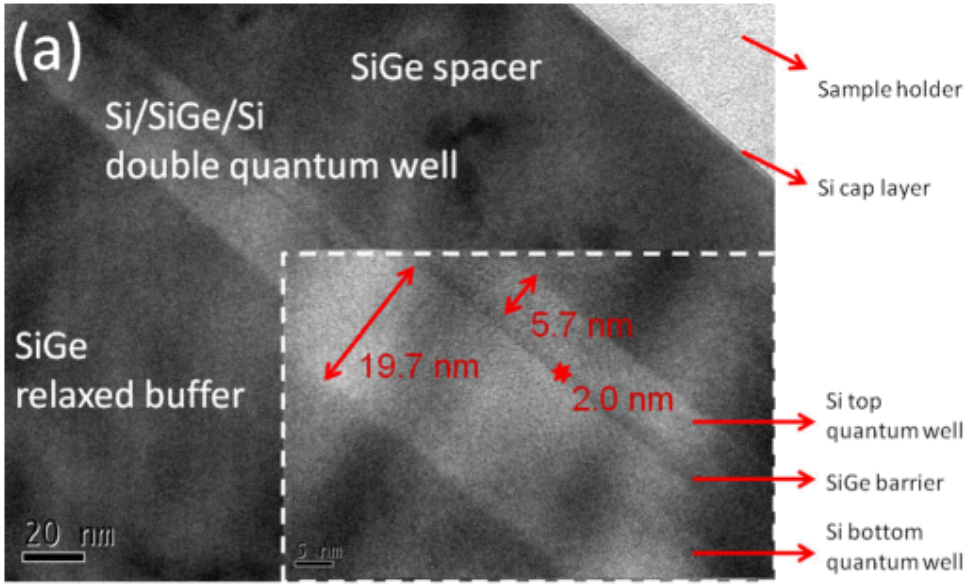
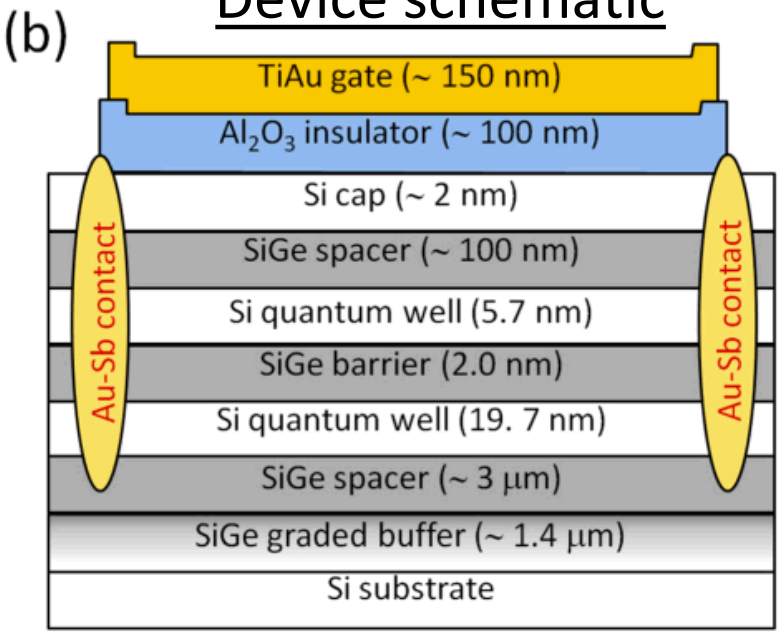
Material and devices

XTEM



Device schematic



Typical HFET structure.
Ohmic contacts are made by annealing Au(1%Sb) on Si.

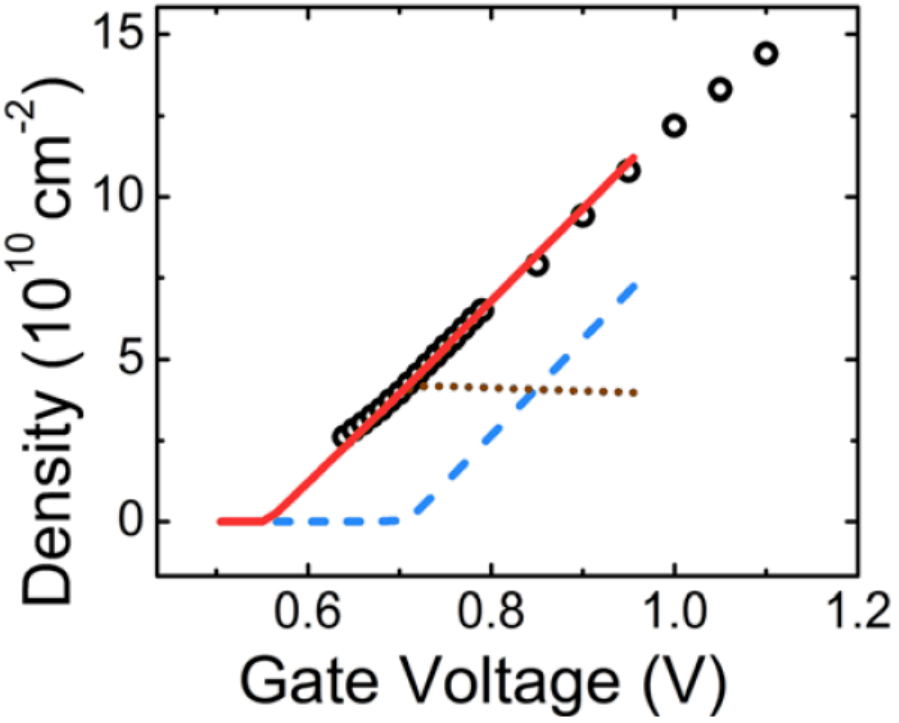
Al_2O_3 is deposited by ALD.

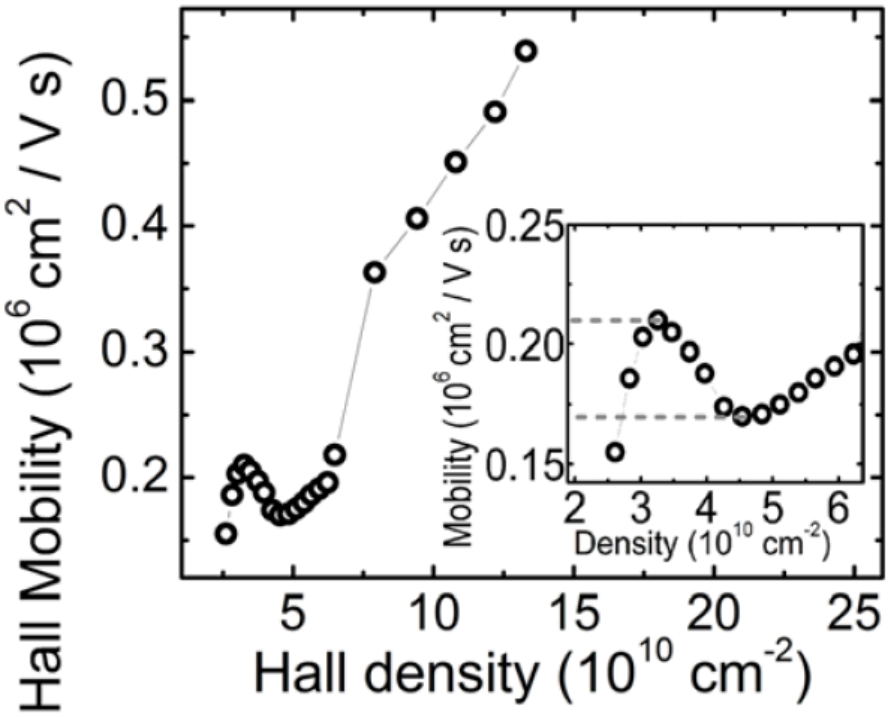
Simulations results shown previously are based on actual thicknesses.

The difference between the target and actual thicknesses are due to non-ideal growth.

The bottom well thickness is relatively unimportant.
The top well thickness is important.

Transport characteristics





T = 0.3 K
No illumination
$I_{excitation}$ = 80 nA @ 13 Hz

Density is extracted from Hall measurement.

Mobility is extracted from ρ|B=0 and the Hall density.

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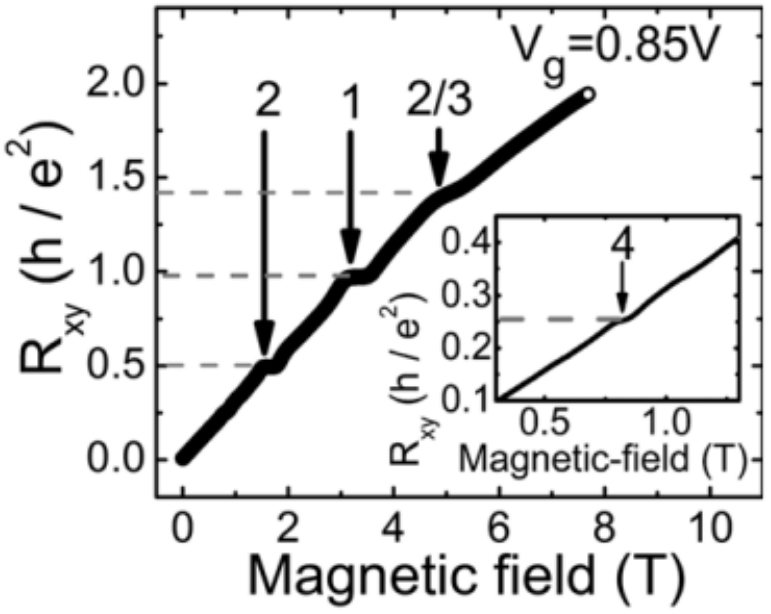
Quantum Hall effect

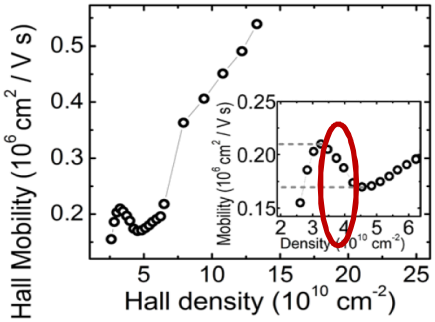


n_{total} ~ 8 x 10^{10} cm^{-2}
Each layer ~ 4 x 10^{10} cm^{-2}

Valley splitting ~ 0.4 K
Δ_{SAS} ~ 1.6 K
Spin splitting ~ 2.2 K @1.6 T assuming g=2
Cyclotron gap ~ 11 K @ 1.6 T

Ideal case:
ν = 8, 16, 24, … are due to cyclotron gaps
ν = 4, 12, 20, … are due to spin gaps
ν = 2, 6, 10, … are due to interlayer tunneling
ν = 1, 3, 5, … are due to valley splitting

We observed the ν = 2 state.



Coulomb energy $e^2/\varepsilon l_B$ ~ 65 Δ_{SAS}
d/l_B ~ 0.7 < 2
Interlayer coherence induced ν = 2 state?

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Future plan

Δ_{SAS} ~ 1.6 K may be too large.

We plan to suppress Δ_{SAS} by using a barrier layer with higher Ge%. (28% instead of 14%).

We will thin the substrate and perform gating from both sides. This will allow better wave function manipulation and eliminate the need for asymmetric quantum well thicknesses.

Conclusion

Demonstrated electron bilayers in undope Si/SiGe:

- A dip in mobility vs density is observed. This signals the onset of a second channel (population of the top quantum well) The crossing density matches simulation results.

- Mobility in excess of 3 x 10^5 cm^2/Vs at approximately balanced densities.

Observed a ν=2 quantum Hall state.

- Energy scale analysis shows that this state could arise from interlayer coherence. However the tunnel couping Δ_{SAS} ~ 1.6 K is high.
- We will further optimize the device for interlayer coherence induced effects.