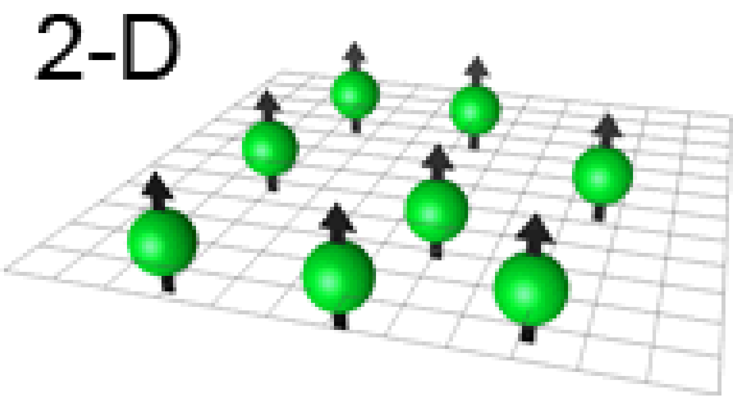
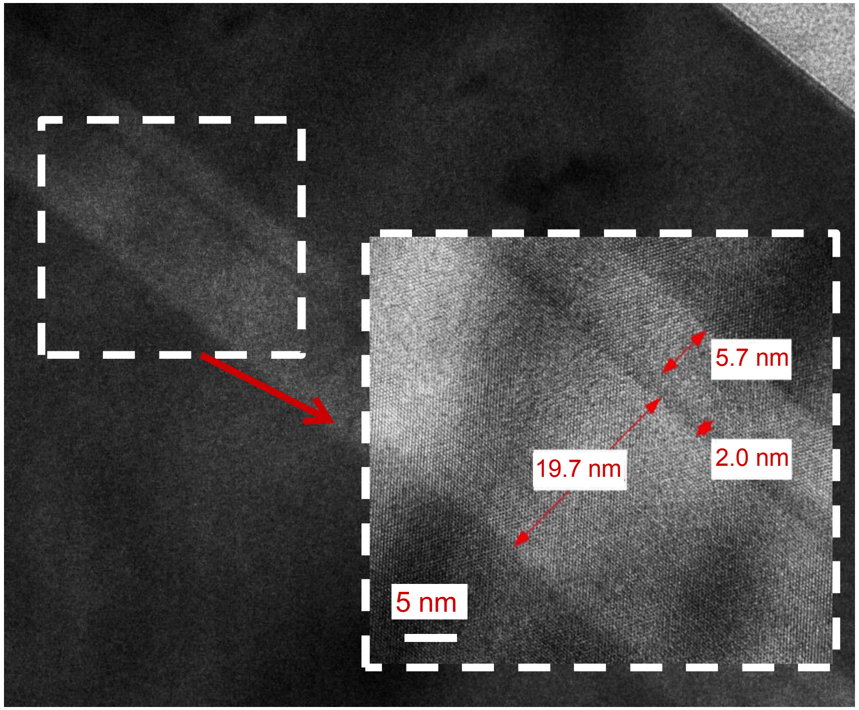
Characterization of undoped Si/SiGe and Ge/SiGe quantum wells

SAND2016-3483PE

Dominique Laroche





QuTech Materials

April 21st 2016

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Sandia National Laboratories

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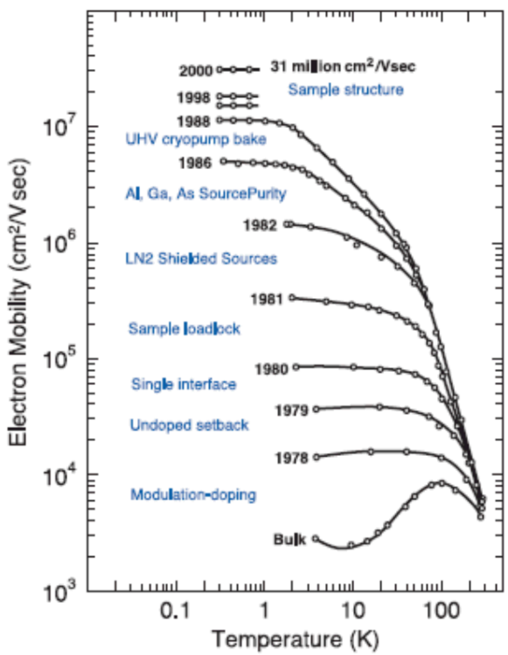
AlGaAs-GaAs high mobility 2DEGs

PHYSICAL REVIEW B
covering condensed matter and materials physics

Limit to two-dimensional mobility in modulation-doped GaAs quantum structures: How to achieve a mobility of 100 million

E. H. Hwang and S. Das Sarma
Phys. Rev. B **77**, 235437 – Published 25 June 2008



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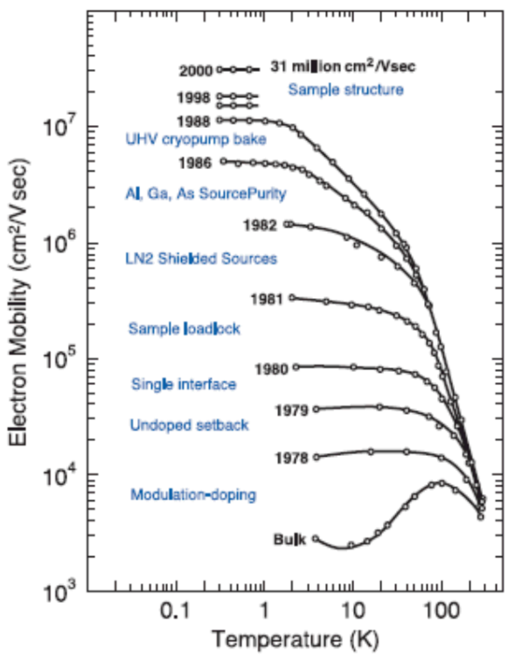

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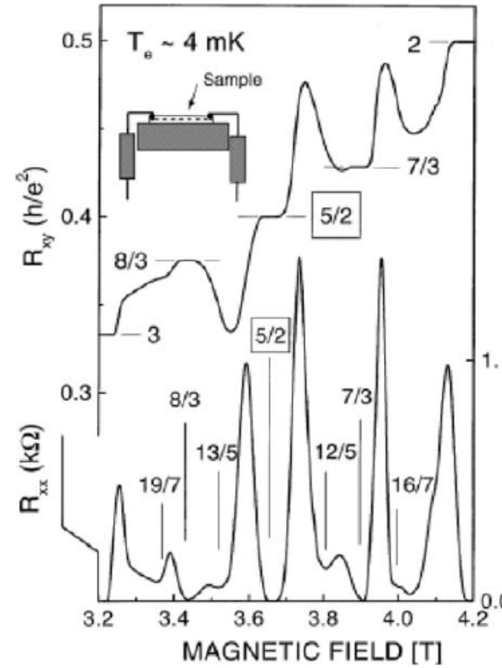

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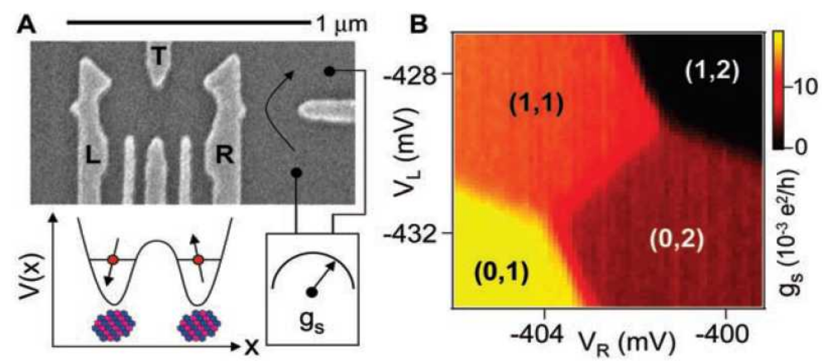

J. R. Petta *et al*. Science 309, 2180 (2005).

GaAs vs. Si based materials

GaAs/AlGaAs structures

High mobility

Presence of a tunable band offset

Deep donors

Large scale integration is problematic

Interactions with nuclear spin bath

Si/SiO_2 Structures

Large scale integration

Natural isotope is nuclear spin free

Shallow donors

Low-mobility

Lack of a tubable band offset

SiGe heterostructures : Can you get the best of both world?

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SiGe heterostructures

Clean interface between SiGe and Si (or Ge) → Improved mobility

Presence of a tunable band offset → Possibility to make quantum wells

CMOS technology compatible → Possibility for large scale integration

Existence of a 0-nuclear spin isotope → Improved relaxation time in quantum-dots

Additional benefit : Strain tunable

Limitations

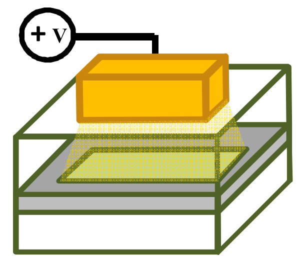
Mobility modest compared to GaAs/AlGaAs
↳ Scattering mechanisms and strain characteristics not fully understood/optimized

Larger electron mass requiring smaller structures
↳ Need for shallower quantum wells

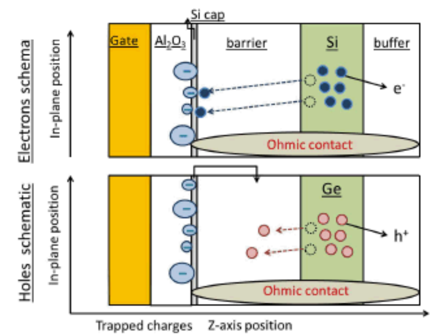
Shallow donors induce additional charge noise in doped structures
↳ Can be avoided using undoped structures

Outline

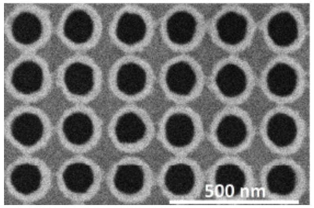
- Capacitively induced 2DEG in shallow Si/SiGe heterostructures
  - Device growth and fabrication
  - Scattering mechanism analysis through mobility vs density dependence
  - Non-equilibrium charge migration model



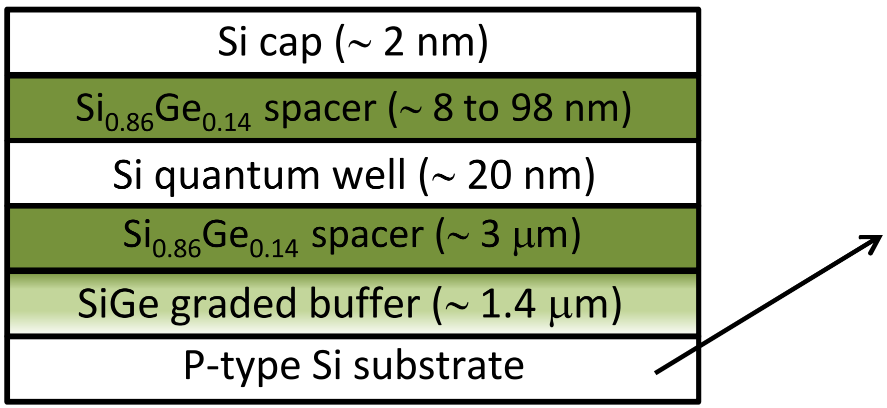
- Capacitively induced 2DHG in Ge/SiGe heterostructures
  - Device growth and fabrication
  - Scattering mechanism analysis through mobility vs density curve
  - Non-equilibrium charge migration model
  - Effective hole mass as a function of density



- More involved possibilities with Si/SiGe heterostructures
  - Artificial disorder/superlattice
  - Electron bilayer



Growth of undoped Si/SiGe heterostructure



Substrate

10 Ω ·cm (room temperature)

Cleaned in 10% HF solution prior to loading in growth chamber.

Growth parameters :

UHVCVD system

Base pressure : 10^{-10} torr

SiH_4 and GeH_4 as precursors

Growth temperature : 550 ° C

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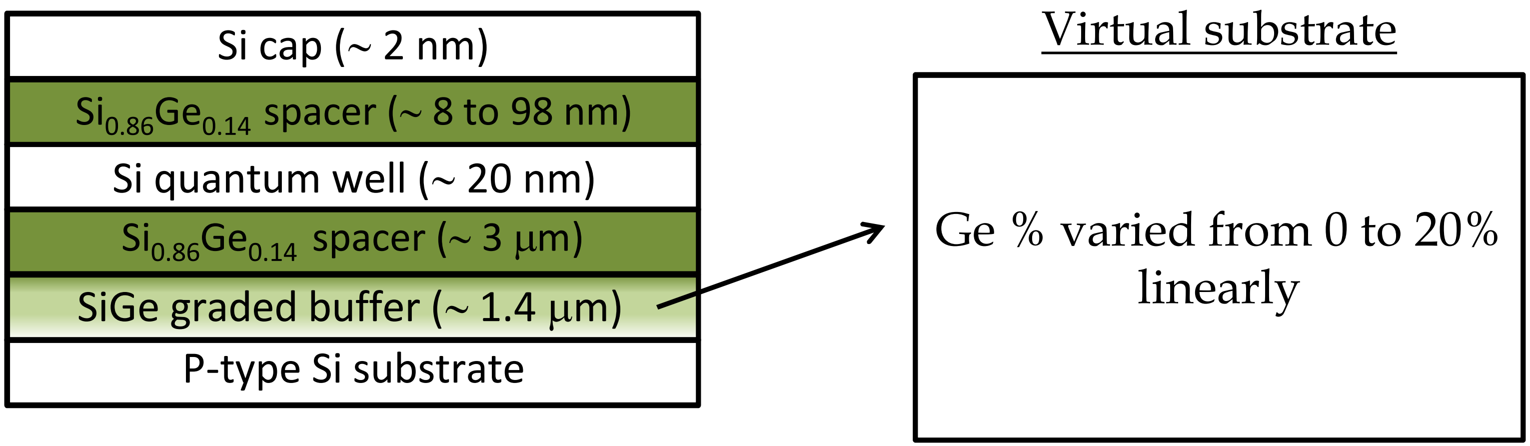
Growth of undoped Si/SiGe heterostructure



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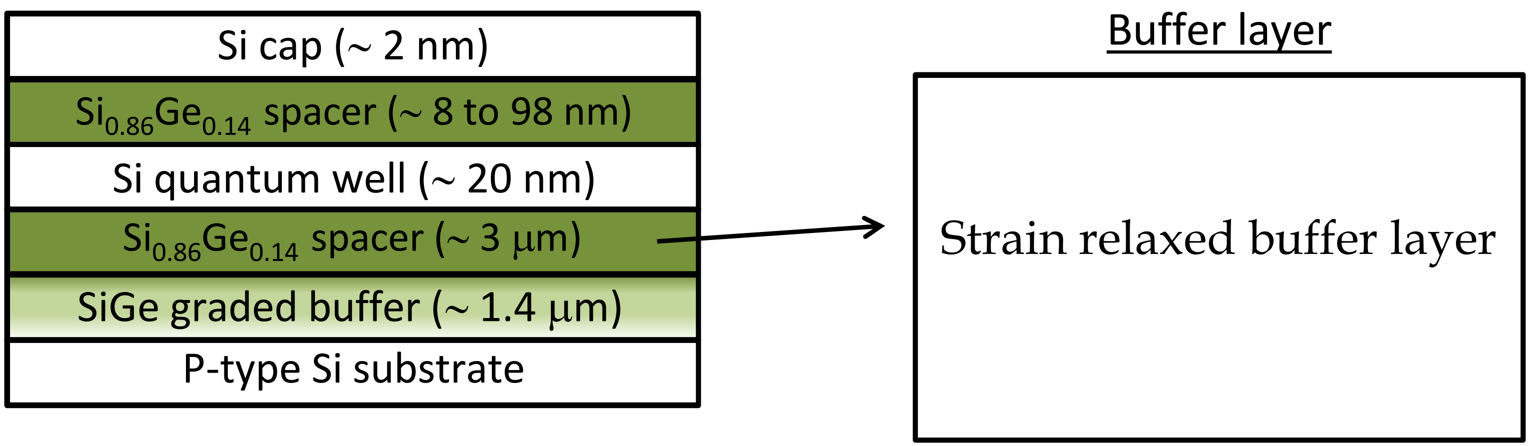

Growth parameters :
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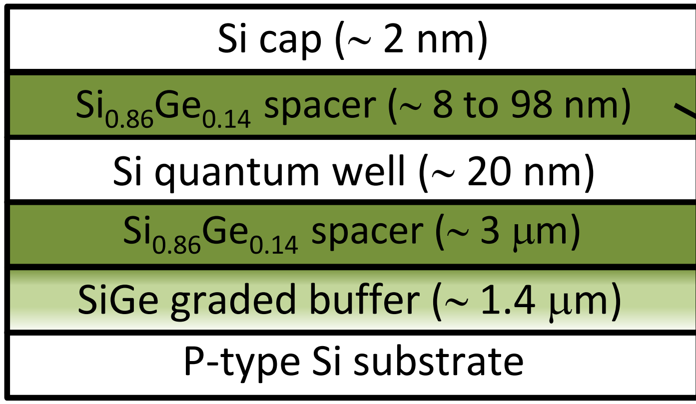
Growth of undoped Si/SiGe heterostructure



Spacer

Series of sample were grown with depth of 10, 25, 50 and 100 nm

Growth parameters :

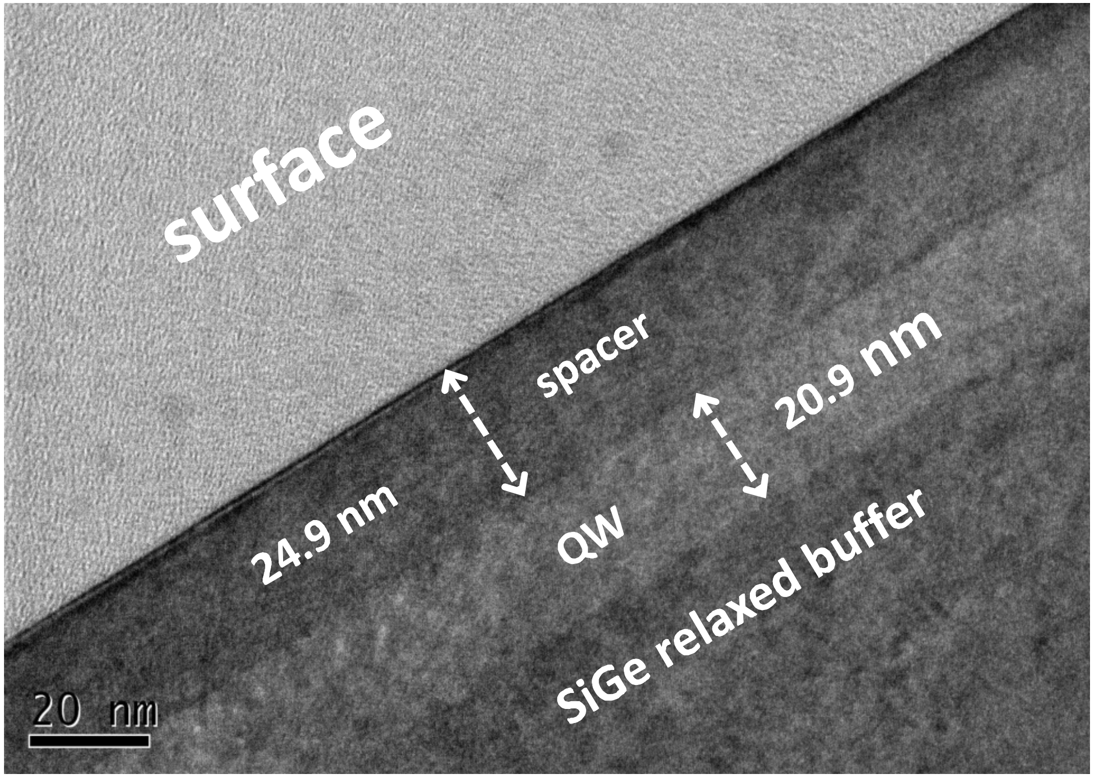
UHVCVD system

Base pressure : 10^{-10} torr

SiH_4 and GeH_4 as precursors

Growth temperature : 550 ° C

Growth of undoped Si/SiGe heterostructure



- Clean interfaces
- Growth dimensions are as expected

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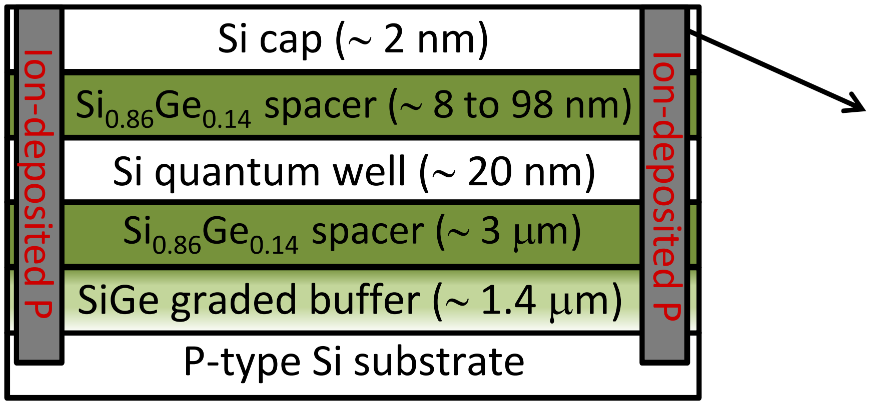
Fabrication of undoped Si/SiGe heterostructure

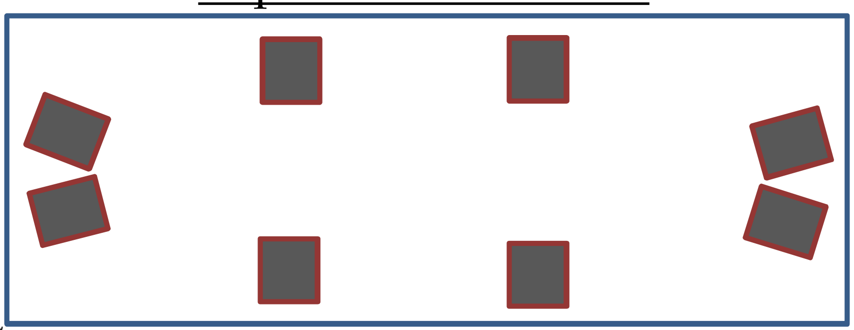
Side view : Schematic



Ion implantation

Ion : Phosphorus
Implant energy : 20 keV and 75 keV
Activation : RTA at 625 ° C for 10 s in formic gas
Contact pads : Ti/Au 20/500Å

Top view : Schematic



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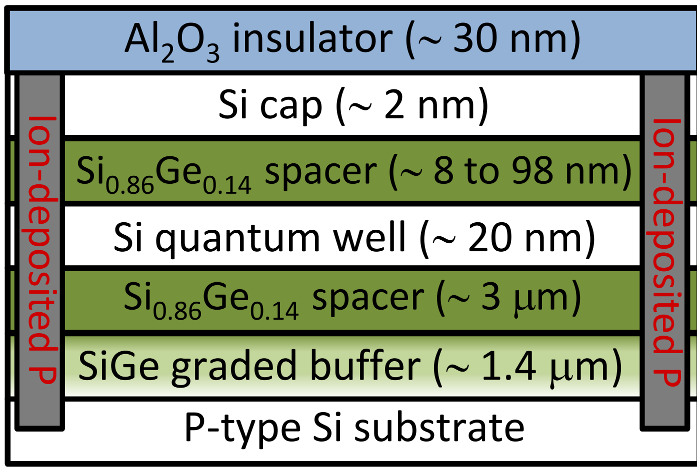
Fabrication of undoped Si/SiGe heterostructure

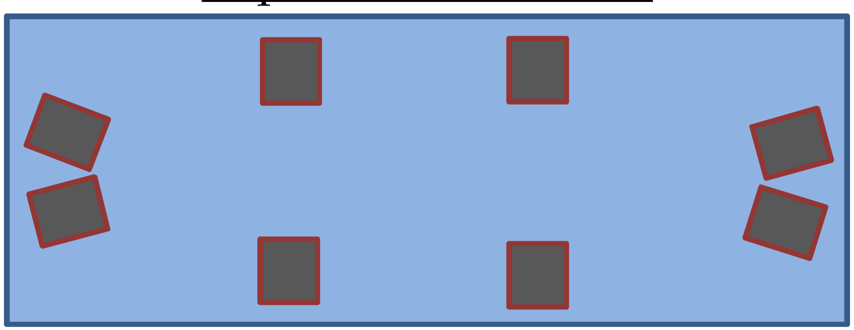
Side view : Schematic



Dielectric layer

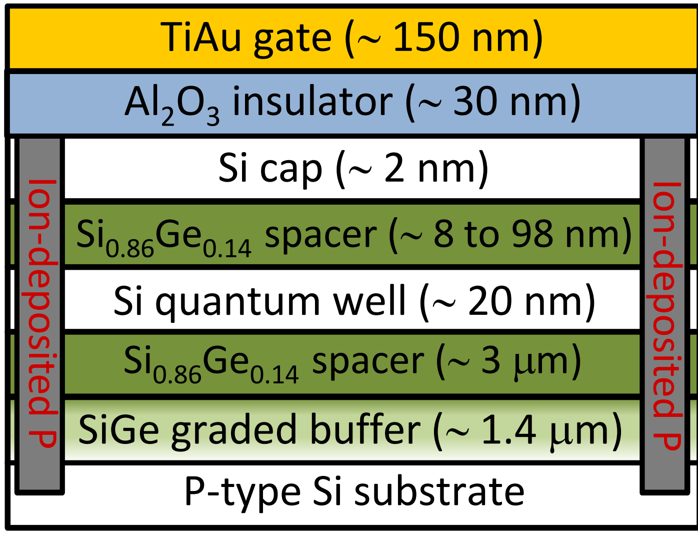
Material : ALD Al_2O_3
Used to isolate the ohmic contacts from the gate

Top view : Schematic



Fabrication of undoped Si/SiGe heterostructure

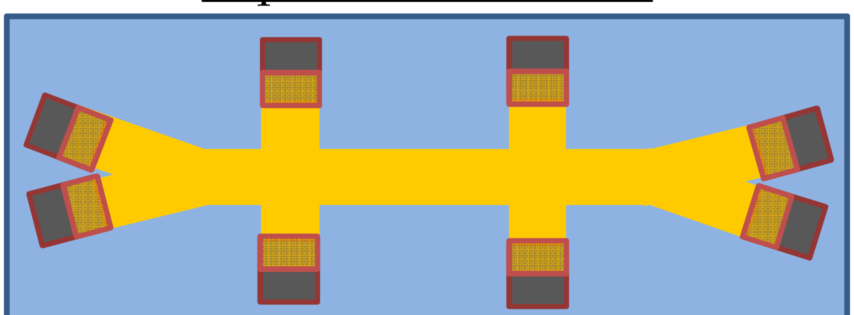
Side view : Schematic



Accumulation gate

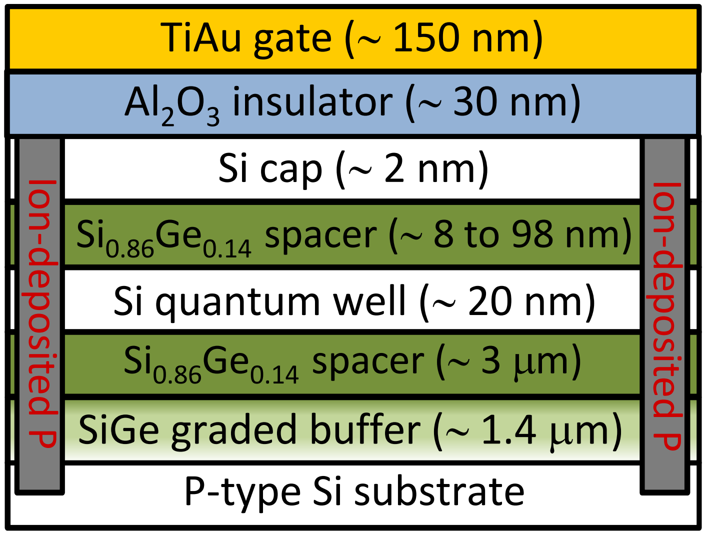
Material : Ti/Au 20/400Å
Used to define a Hall bar

Top view : Schematic

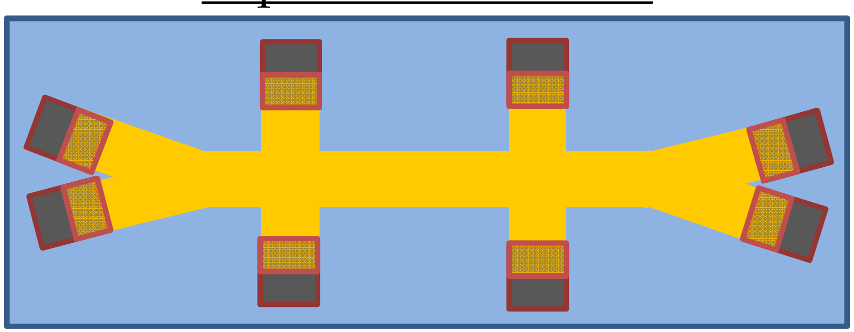


Undoped Si/SiGe HFETS

Side view : Schematic



Top view : Schematic



Process optimized for high mobility structures

APPLIED PHYSICS LETTERS **94**, 182102 (2009)

Observation of two-dimensional electron gas in a Si quantum well with mobility of 1.6×10^6 cm^2/V s

T. M. Lu,[1,a)] D. C. Tsui,[1] C.-H. Lee,[2] and C. W. Liu[3]

Mobility : ≈ 1.6 cm^2 / V·s
Dielectric : Al_2O_3
2DEG depth : ≈ 65 nm
Ohmic contacts : AuSb alloy

APPLIED PHYSICS LETTERS **106**, 092102 (2015)

Ultra-high mobility two-dimensional electron gas in a SiGe/Si/SiGe quantum well

M. Yu. Melnikov,[1,a)] A. A. Shashkin,[1] V. T. Dolgopolov,[1] S.-H. Huang,[2] C. W. Liu,[2,b)] and S. V. Kravchenko[3]

Mobility : ≈ 2.4 cm^2 / V·s
Dielectric : SiO_2
2DEG depth : ≈ 150 nm
Ohmic contacts : AuSb alloy

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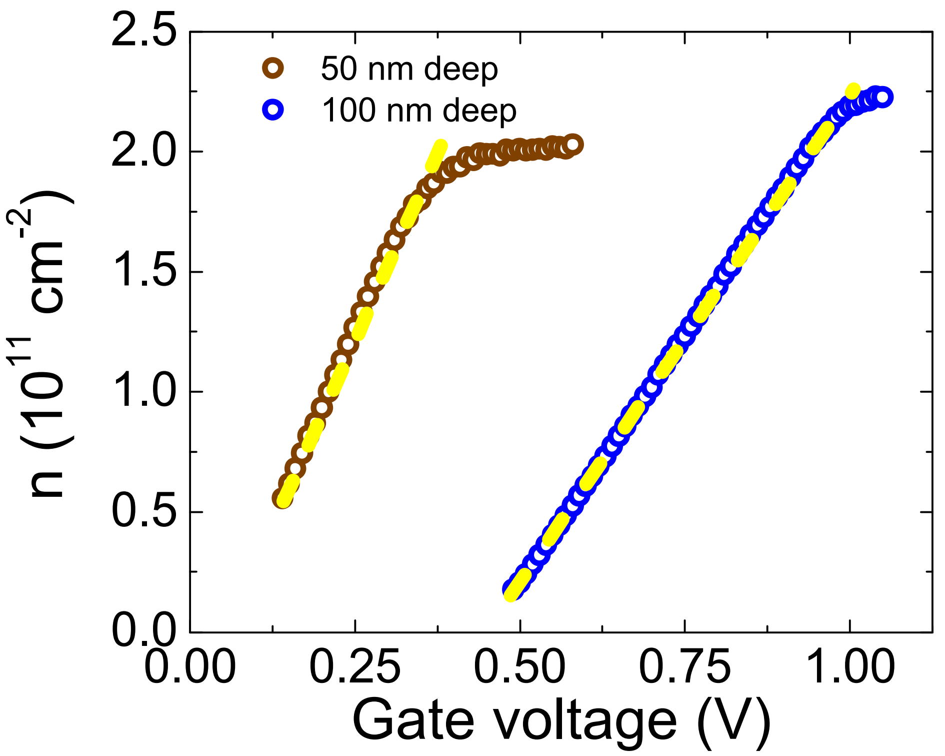
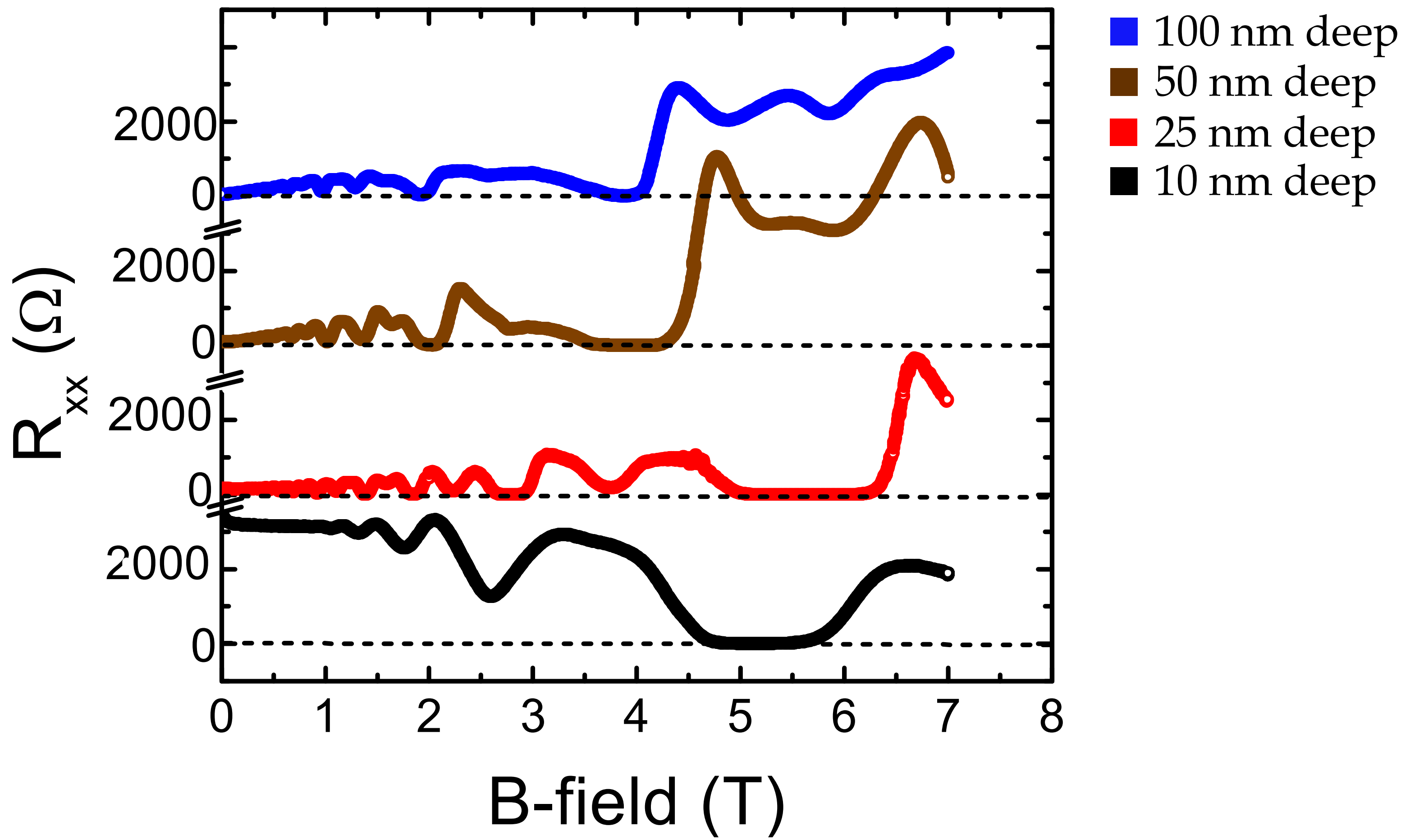
Density vs gate voltage



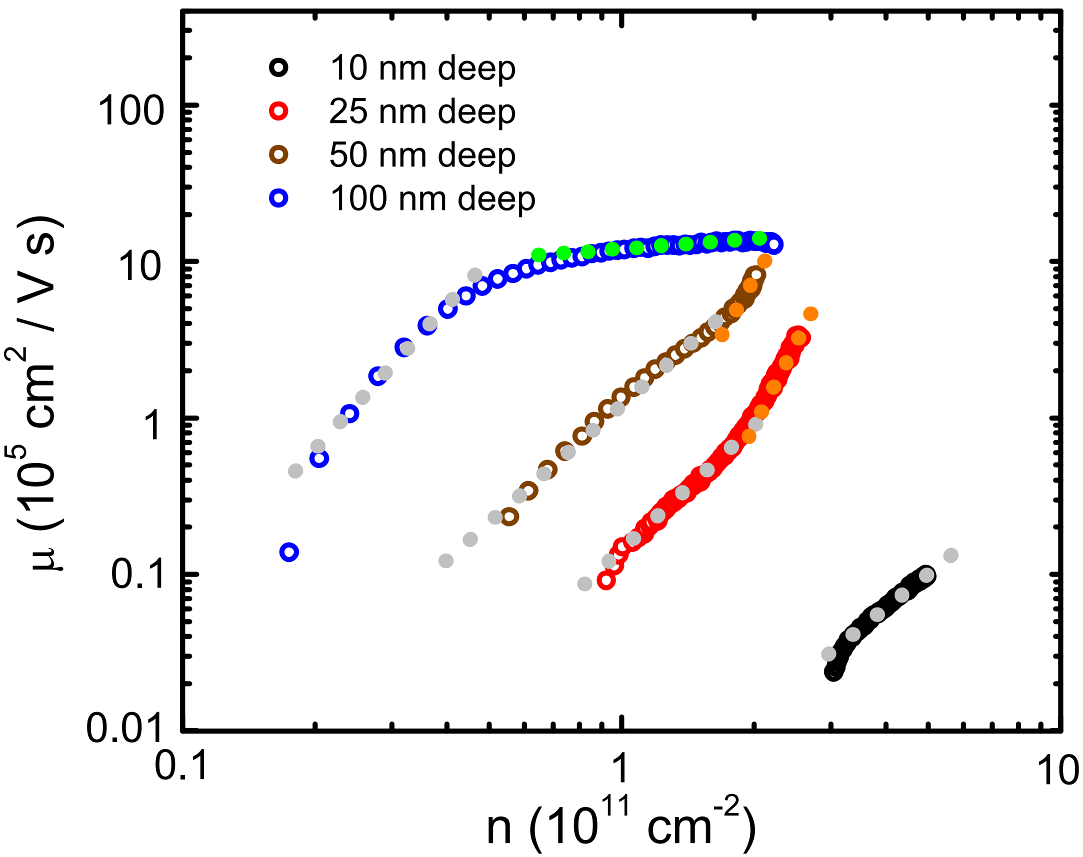
- Low gate voltage : Consistent with parallel plate capacitor model
- High gate voltage : Saturation of the electron density

Initial R_{xx} characterization



- Clean R_{xx} traces are observed for all 2DEGs depth
- Good sample quality down to 10 nm depth

Density versus mobility



Mobility of ~ 3 x 10^5 cm^2 / V · s is achieved in 25 nm deep devices

- Intermediate density : $\mu \sim n^{\alpha}$; $\alpha \sim 2.5$
  - ➢ Remote charged impurities dominate scattering. Low-density corrections to the RPA model have to be considered.
- High density, deep device : $\mu \sim n^{\alpha}$; $\alpha \sim 0$
  - ➢ Interface roughness is increasing
- High density, shallow devices : $\mu \sim n^{\alpha}$; $\alpha \sim 5$
  - ➢ Non-standard scattering mechanism.

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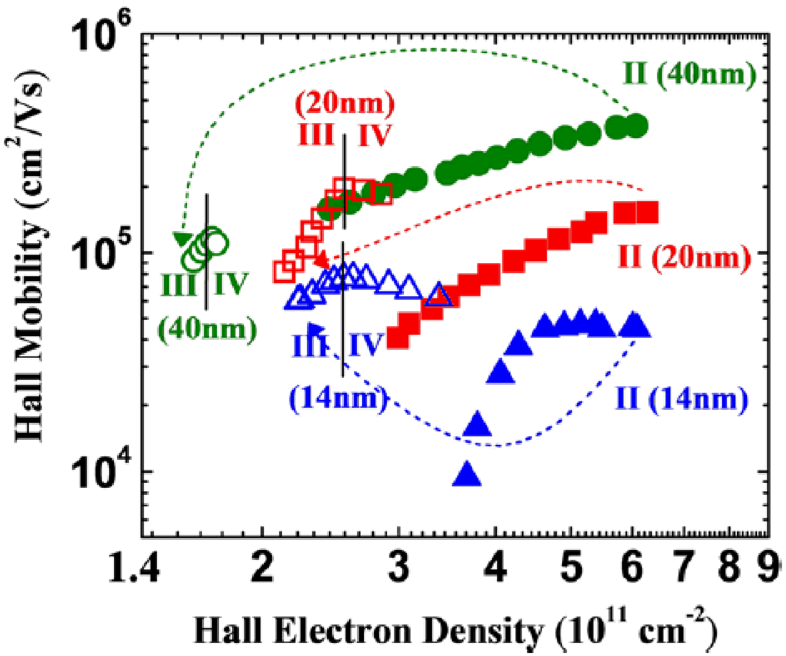
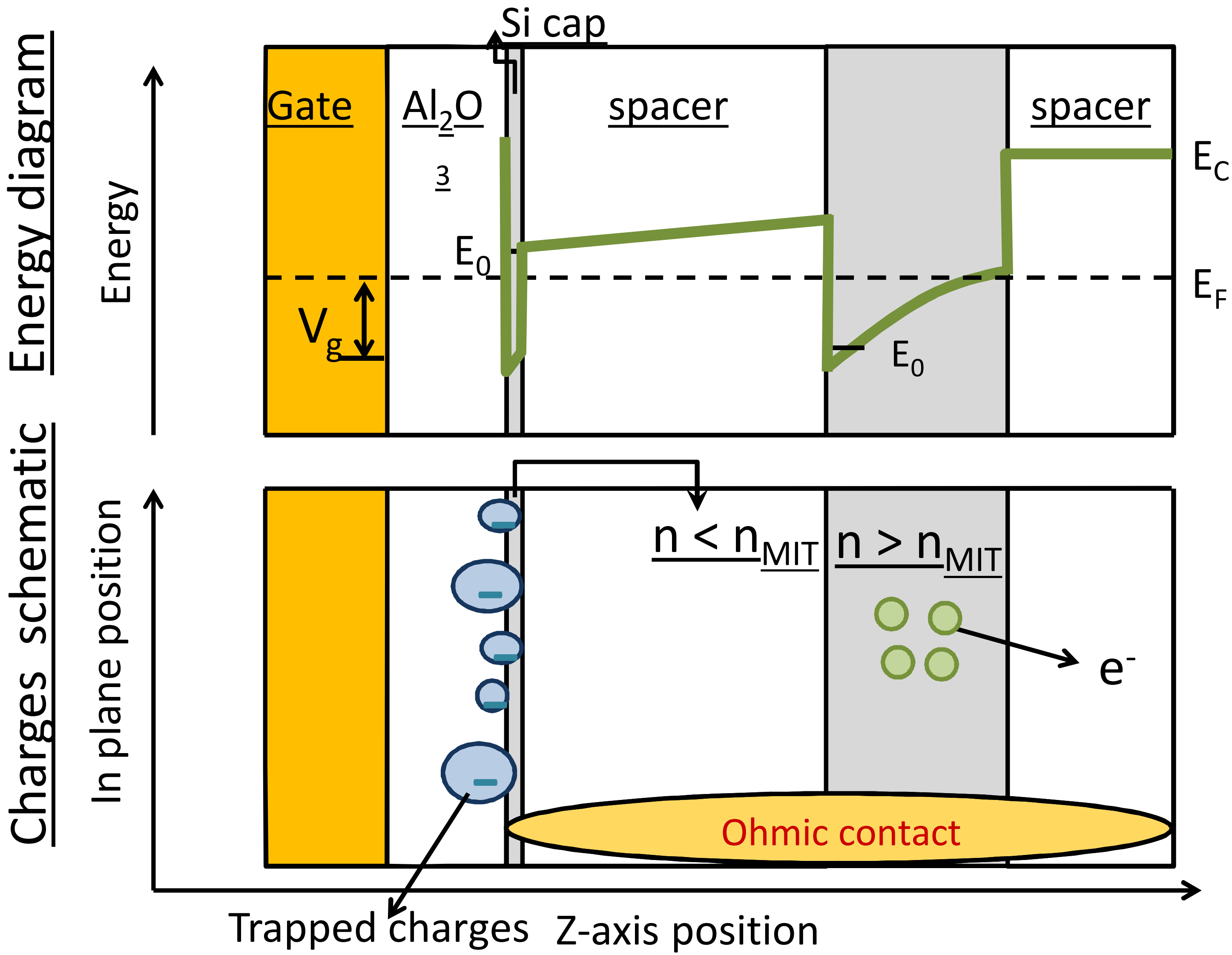
Non-equilibrium charge migration

- There is a 2nd narrow QW at the surface
  - ⮡ Becomes the ground state at high enough V_g
- Large concentration of defects near the surface
  - ⮡ Electrons can't flow from contacts to surface QW. Non-equilibrium situation
- Electrons can tunnel from buried to surface QW
  - ⮡ Form a shielding layer near the surface

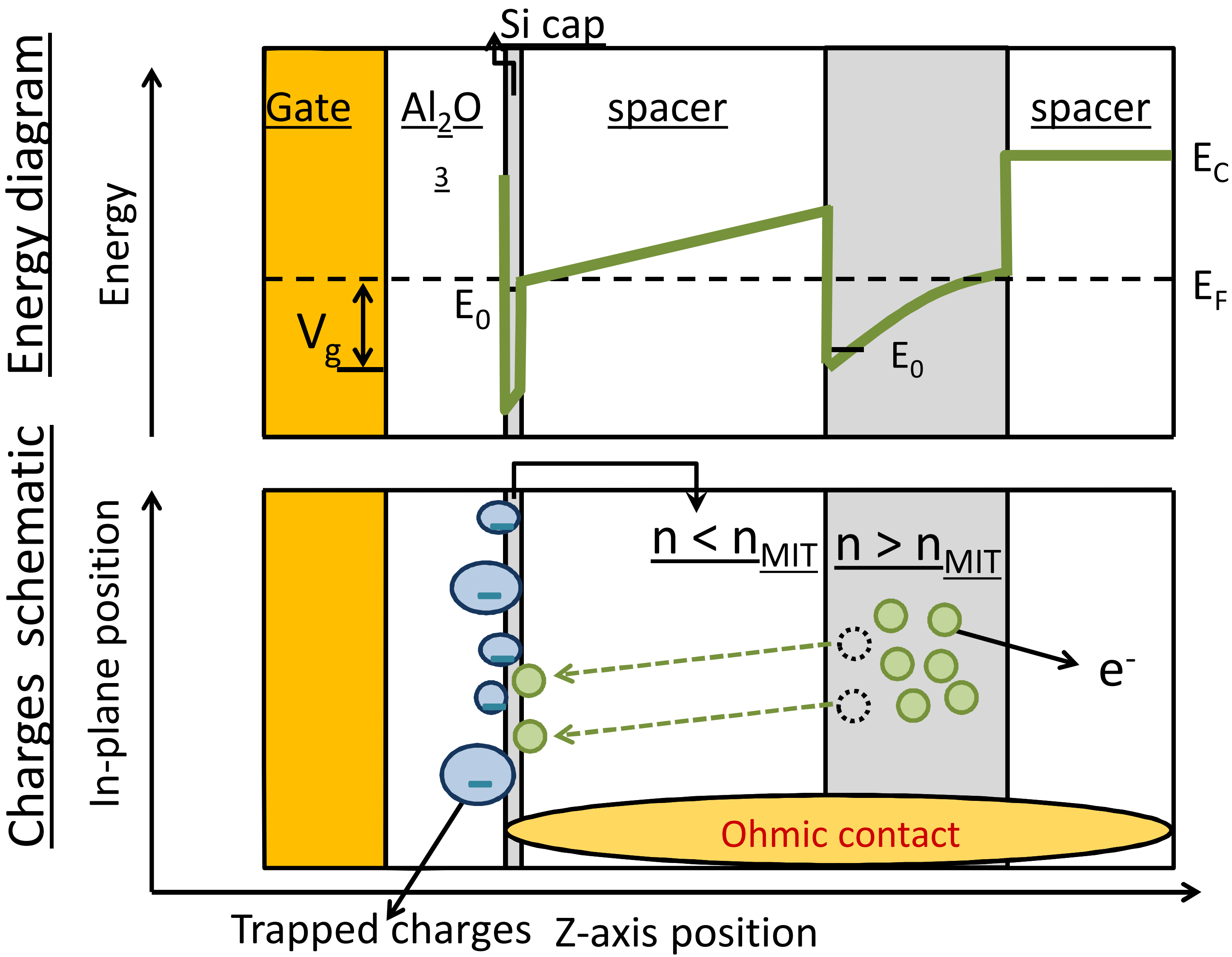


C.-T. Huang *et al.* APL **104**, 243510 (2014).

Non-equilibrium charge migration



Non-equilibrium charge migration



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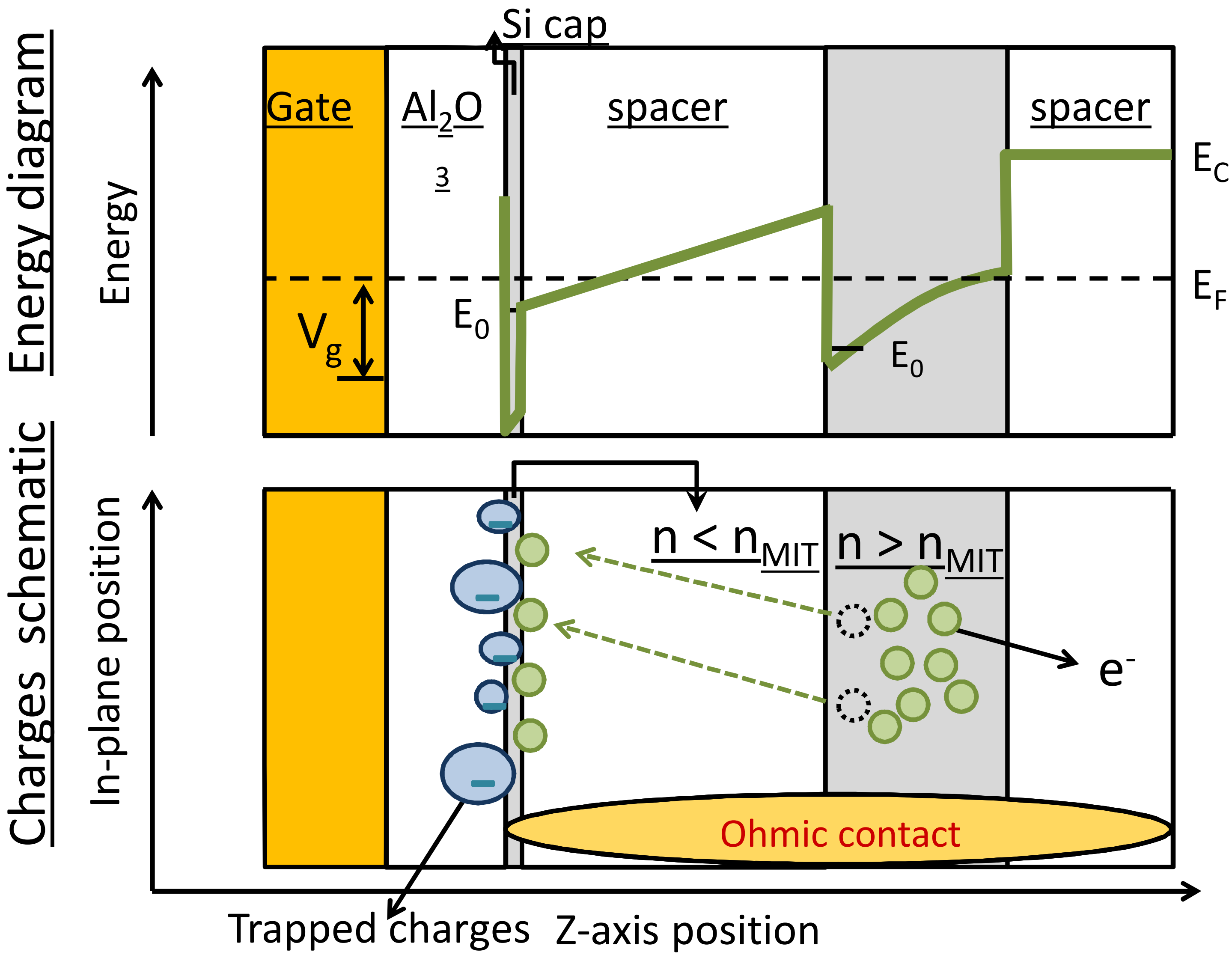
Non-equilibrium charge migration



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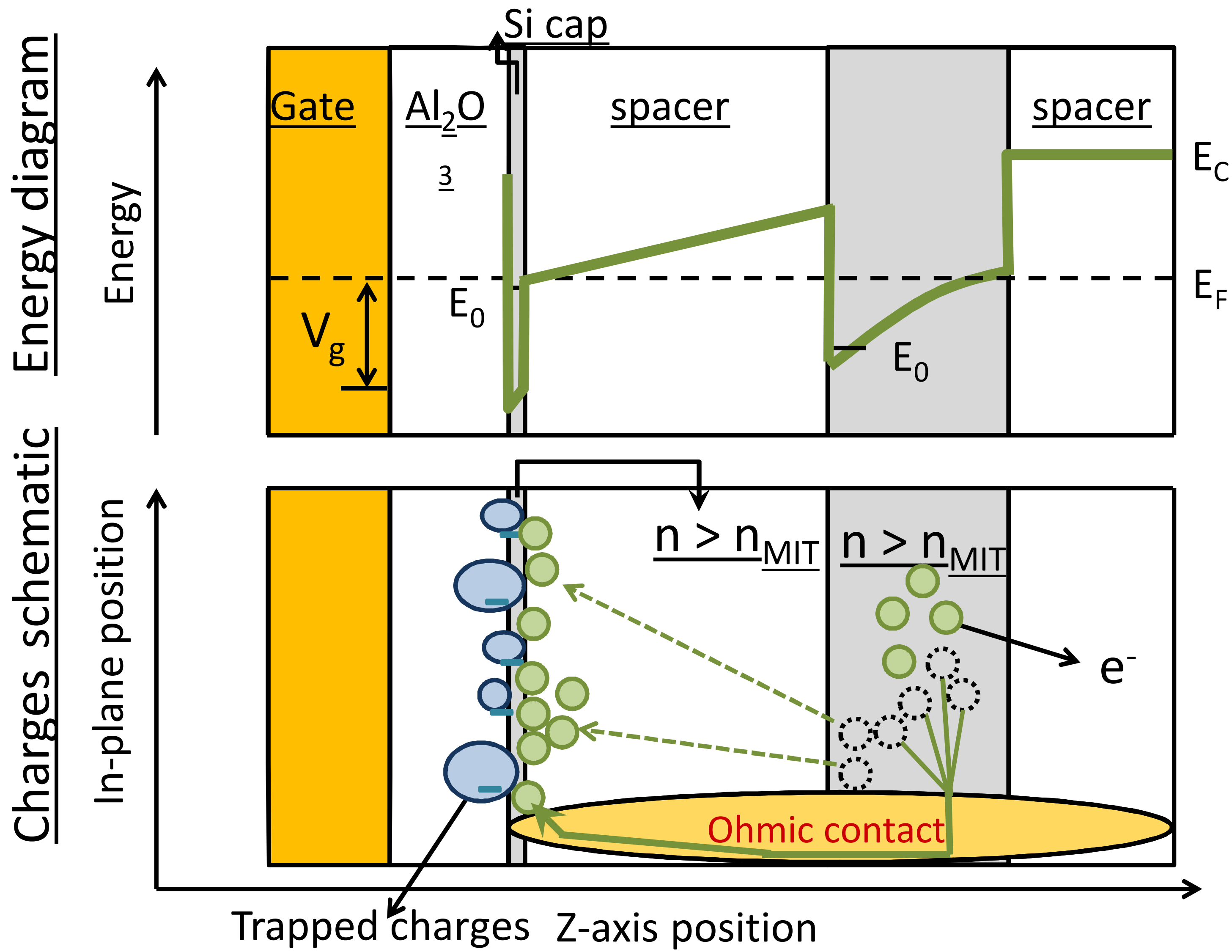
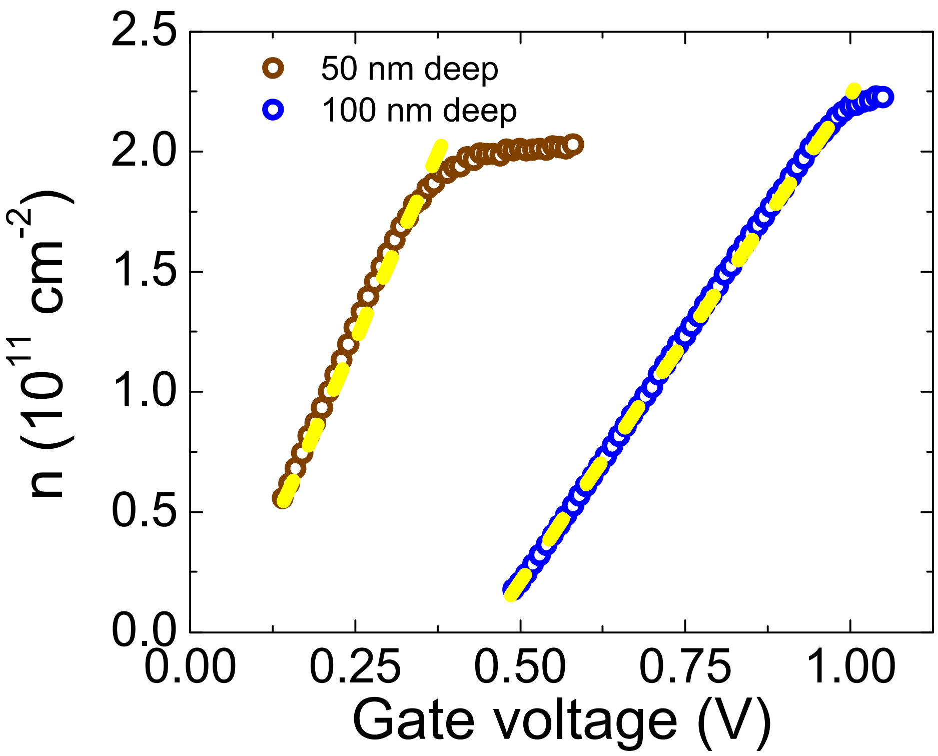
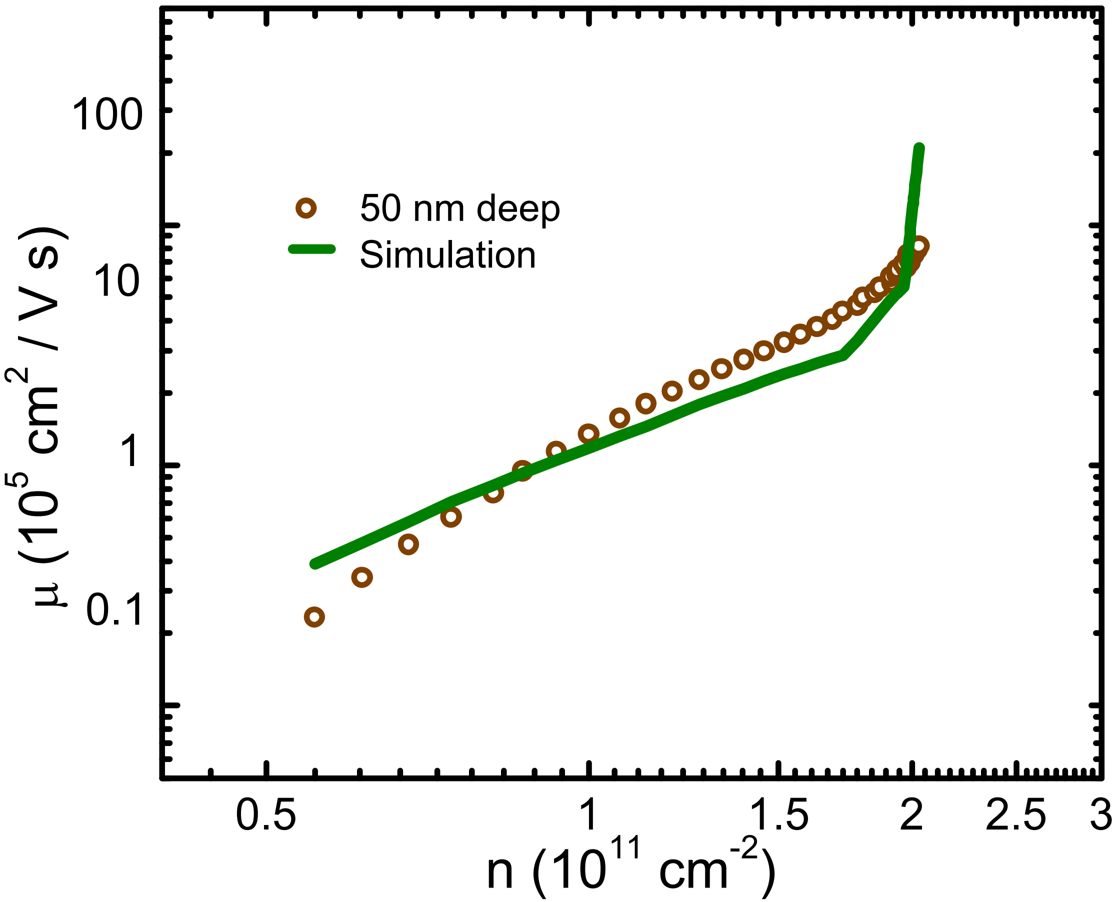


Density vs gate voltage



- Low gate voltage : Consistent with parallel plate capacitor model
- High gate voltage : Saturation of the electron density

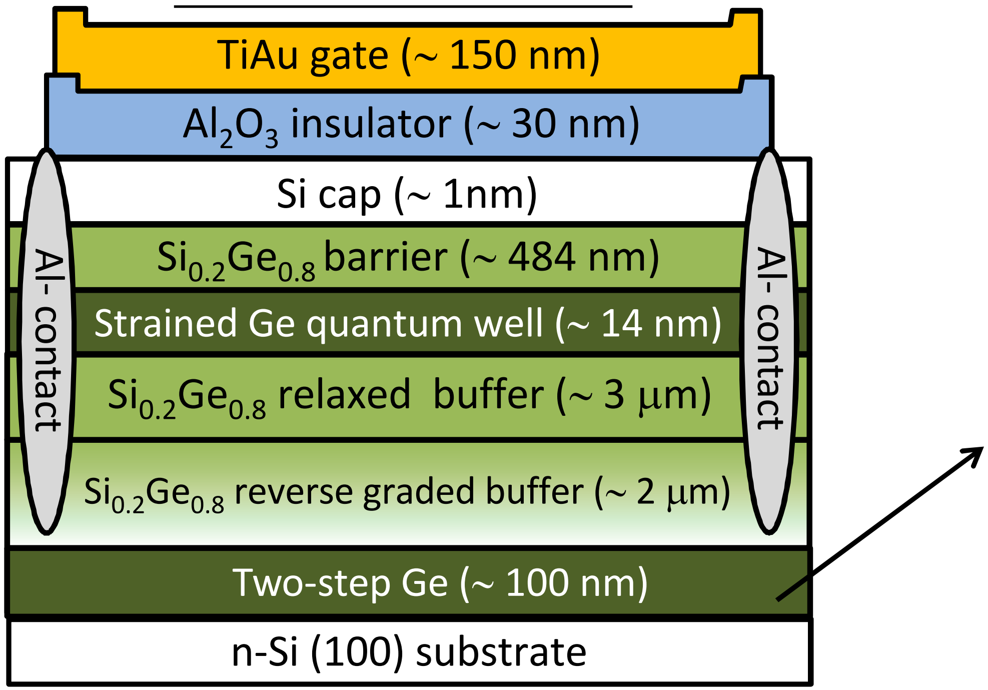
Comparison to experiment



- ➢ Amount of migration charge determined from density vs. gate voltage curve
- ➢ Qualitatively reproduces the data
- ➢ Including low density corrections to the RPA model would need to be considered for better accuracy

Undoped Ge/SiGe HFETS

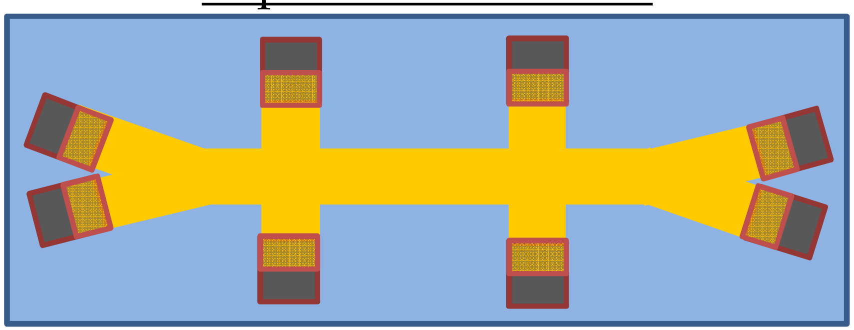
Side view : Schematic



Two-step Ge

Serves as virtual substrate
Strain and dislocations are located away from the 2DEG

Top view : Schematic



APPLIED PHYSICS LETTERS 101, 172108 (2012)

Ultra-high hole mobility exceeding one million in a strained germanium quantum well

A. Dobbie,[a] M. Myronov, R. J. H. Morris, A. H. A. Hassan, M. J. Prest, V. A. Shah, E. H. C. Parker, T. E. Whall, and D. R. Leadley
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

Can it get better in undoped systems?

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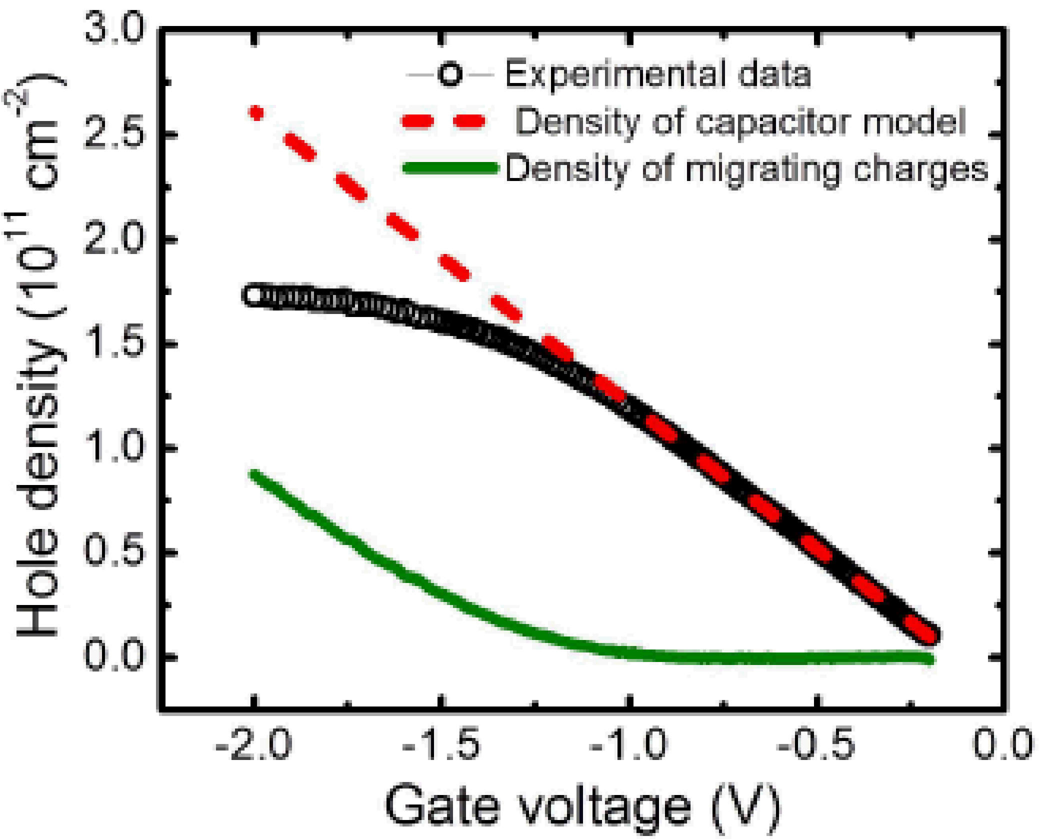
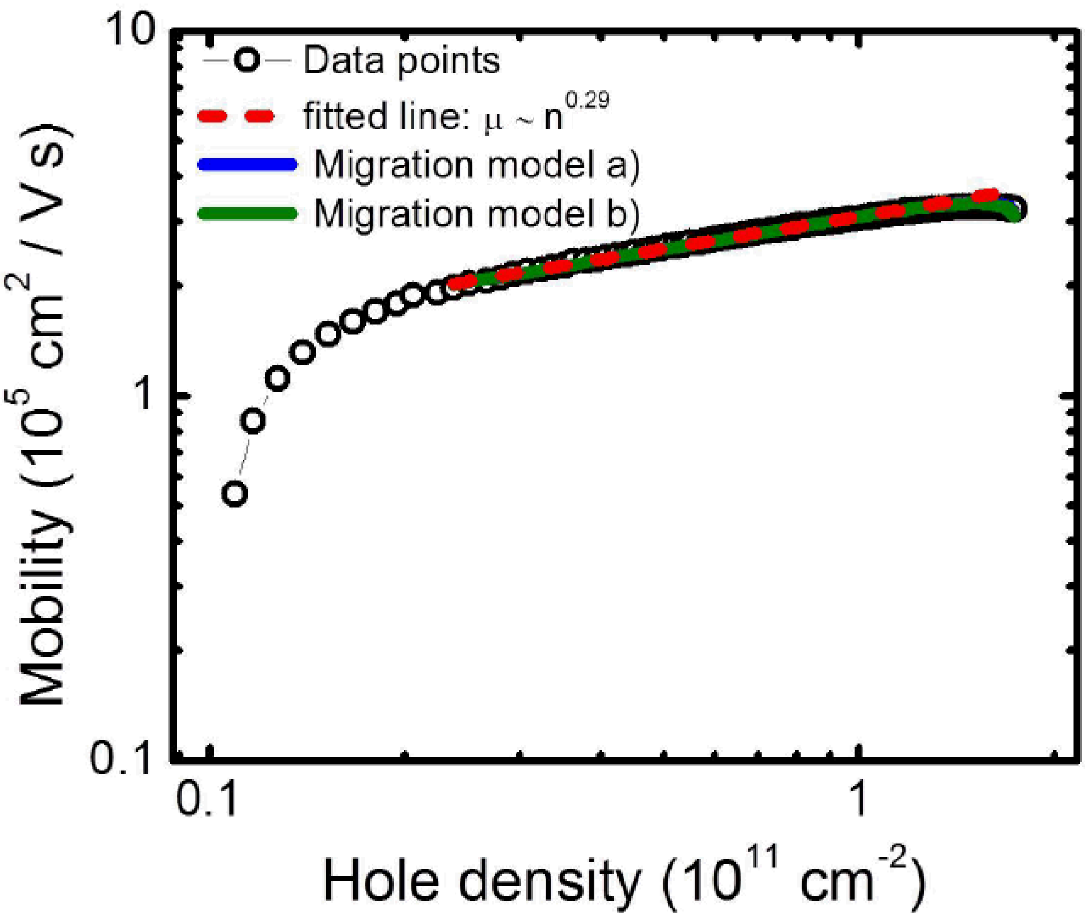
Density vs gate voltage



- Similar to Si/SiGe systems
- Get charge migration at large magnitude of gate voltage
- Much lower density than in doped systems is achievable

Density versus mobility



Intermediate density regime :

$\mu \sim n^{\alpha}$; $\alpha \sim 0.29$: Background charged impurity scattering

High density regime :

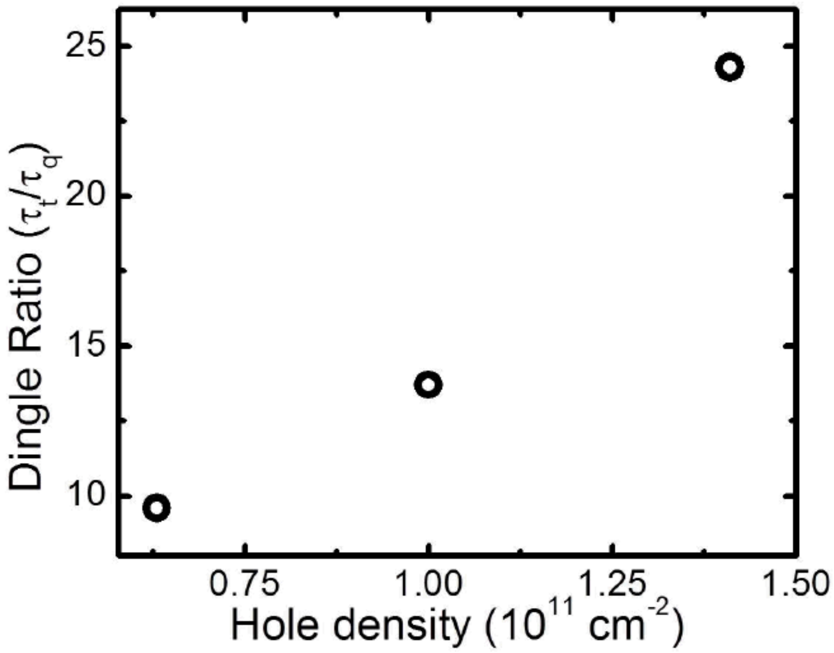
Saturation of the mobility → at lower value than in doped systems

Dingle ratio analysis

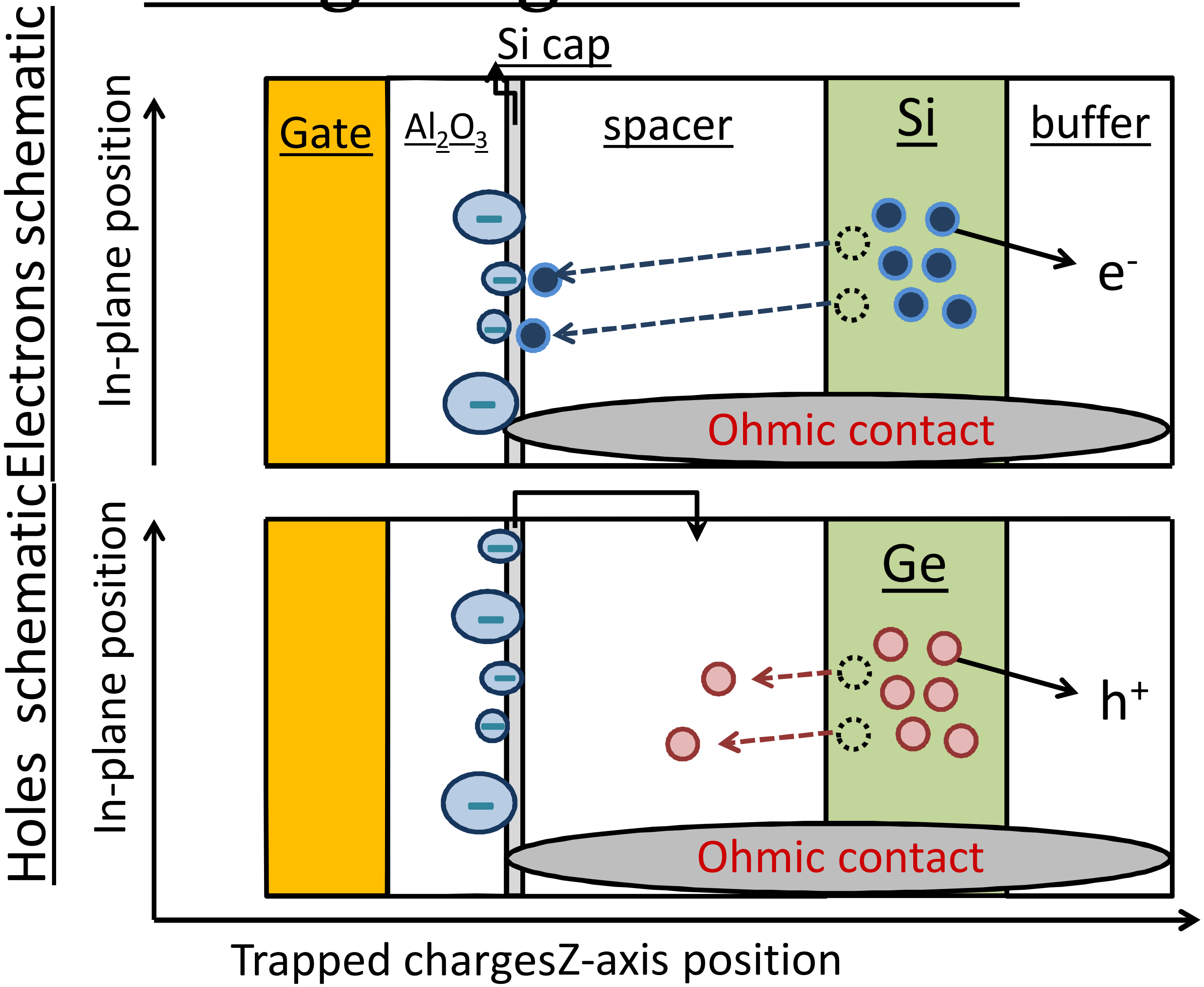
Dingle ratio : τ_t / τ_q

Small dingle ratio : Large angle scattering
→ Disorder in close to the 2DHG
Large dingle ratio : Small angle scattering
→ Remote disorder

Dingle ratio increases with density
- Inconsistent with interface roughness scattering
- There is an increase in the remote charged disorder
- This results in a mobility drop



Charge migration model



Could be explained by charge migration model
→ Need charges to get trapped inside the spacer

Simulation results

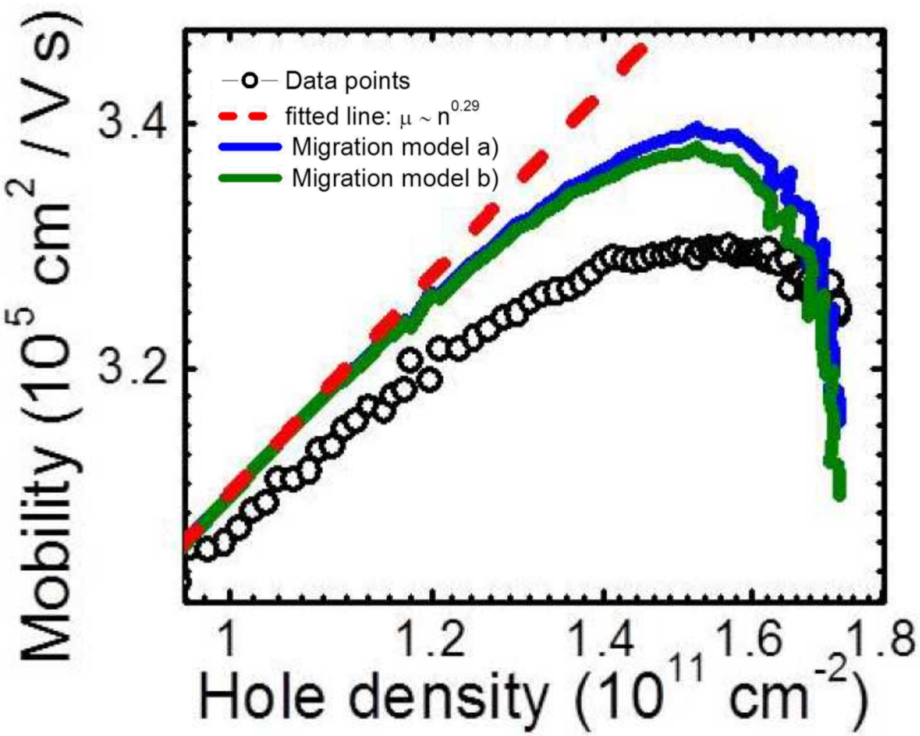
Assumption

- All initial scattering mechanisms are included in $\mu \sim n^{0.29}$
- Migrating charges are treated as remote charge centers within RPA approximation
- Combine scattering mechanism using Matthiessen's rule

Optimize for

a) All migrating charges at a fixed distance from the 2DHG

b) Migrating charges evenly spaced after a cut-off distance from the 2DHG



Good agreement between data and charge migration model

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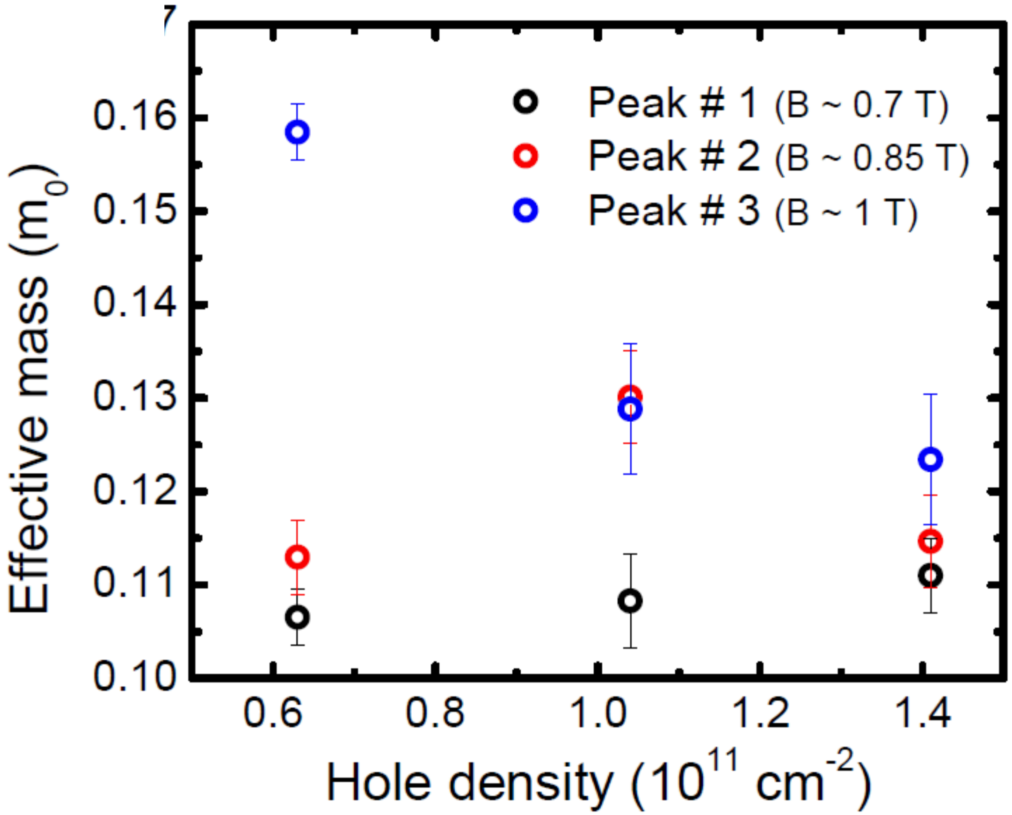
Effective mass



- Obtained from T-dependence of R_{xx} oscillation amplitude
- Much higher than what is expected from measurement at high density in doped-structure

Explanation

- Low-density effect?
- Strain difference between doped and undoped structures?

Reference	doping	Ge content	density	measured mass	extrapolated mass
This work	No	80%	1×10^{11} cm^{-2}	0.105 m_0	—
Irisawa *et al.*	Yes	70%	5.7×10^{11} cm^{-2}	0.087 m_0	$\sim$ 0.07 m_0
Rössner *et al.*	Yes	70%	2.9×10^{11} cm^{-2}	0.095 m_0	$\sim$ 0.085 m_0
Hassan thesis	Yes	80%	2.9×10^{11} cm^{-2}	0.063 m_0	—

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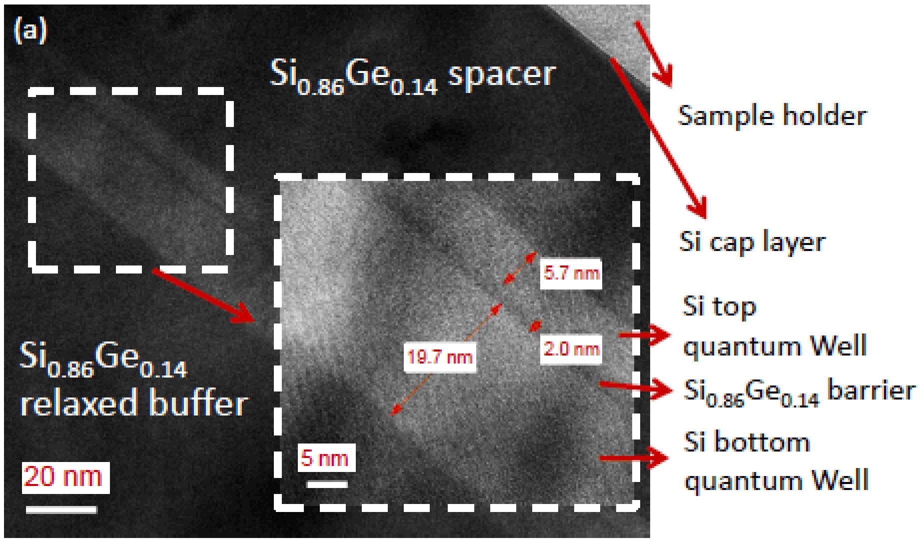
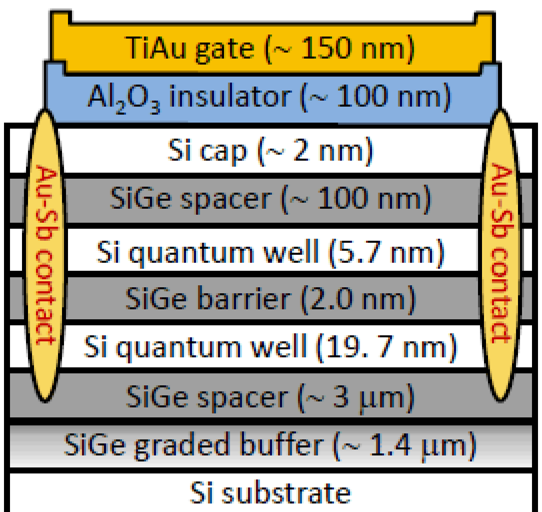
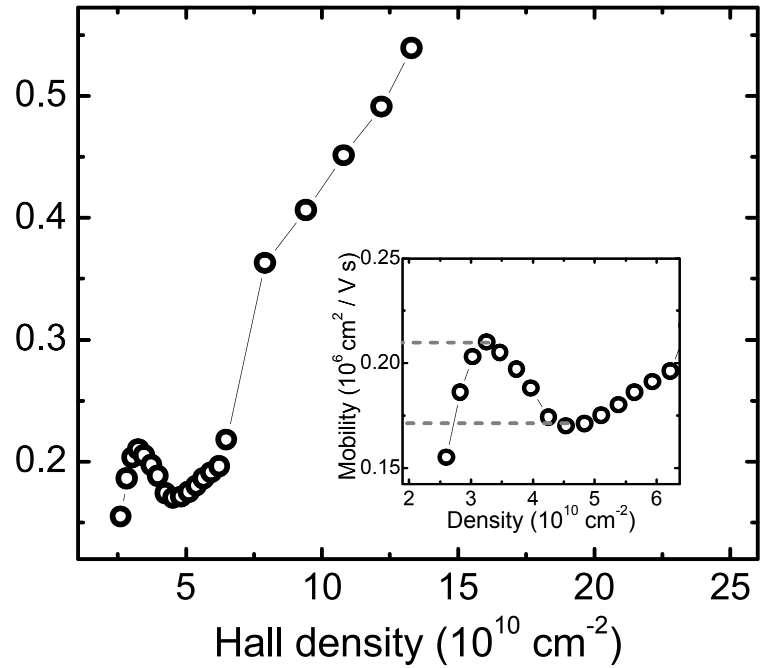
Si/SiGe bilayer

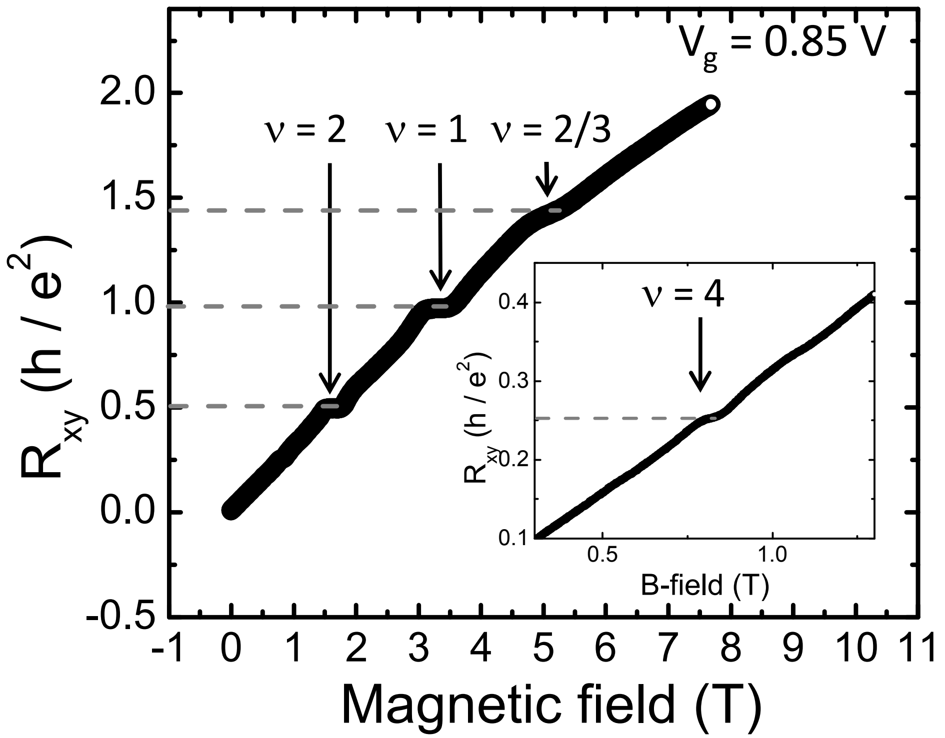






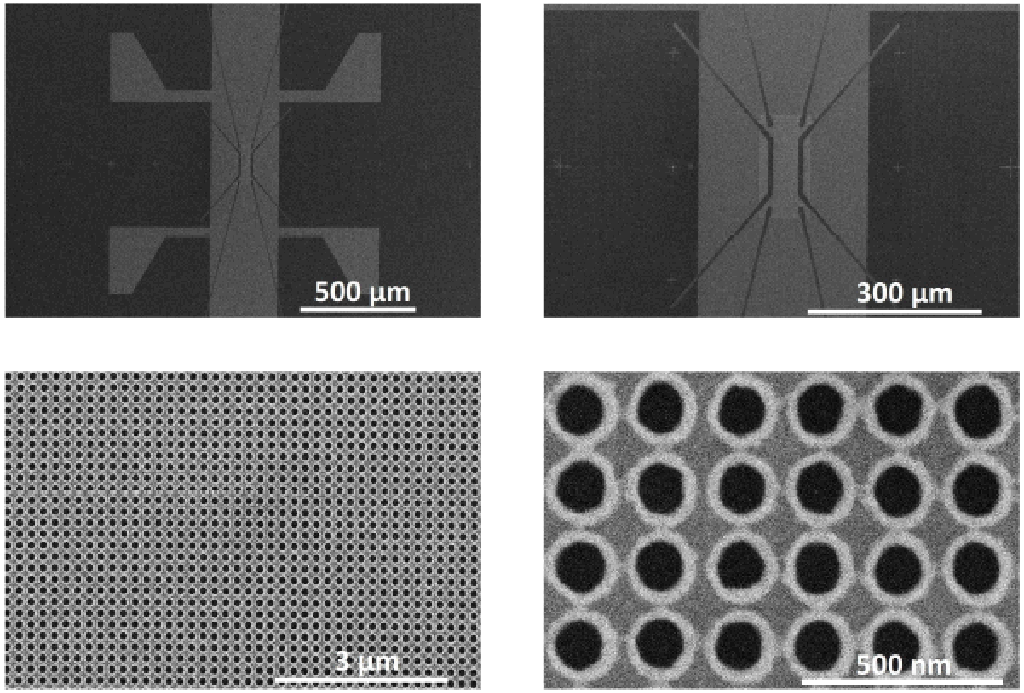
- ➢ Cannot be done in doped systems
  - ⮡ Dopants surface segregation
- ➢ Use asymmetric quantum well
  - ⮡ Maximal density in lower well is fixed
- ➢ Back gating would increase tunability of system

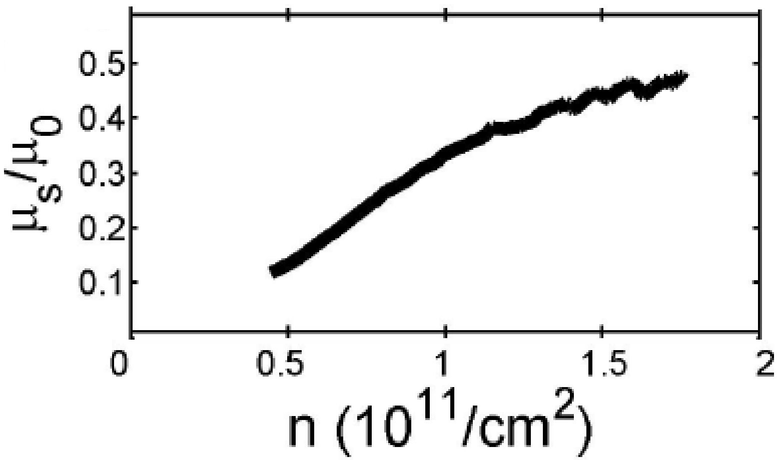
Si/SiGe bilayer



- ν_{tot} integral and fractional Hall states are observed.
- Parameters need to be tuned to distinguish between interlayer coherence or Δ_{SAS} coupling

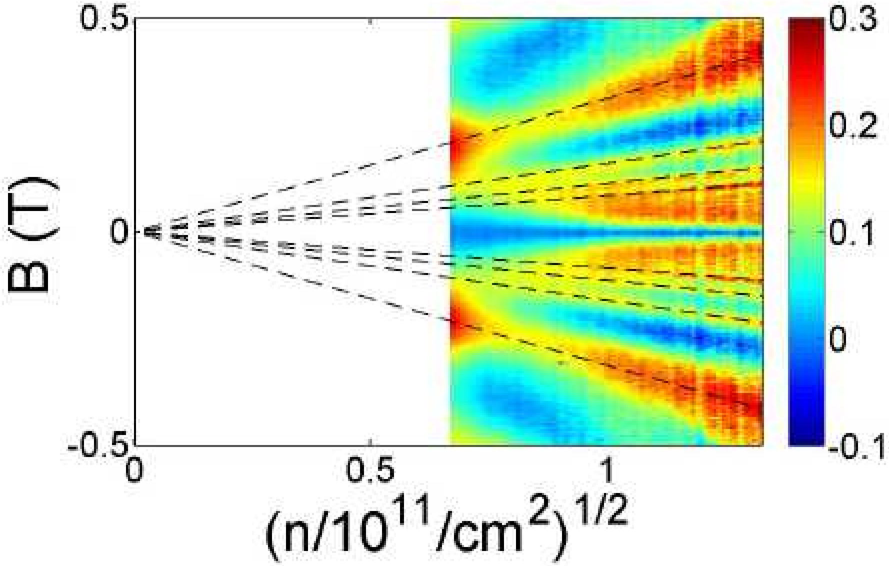
Artificial superlattice

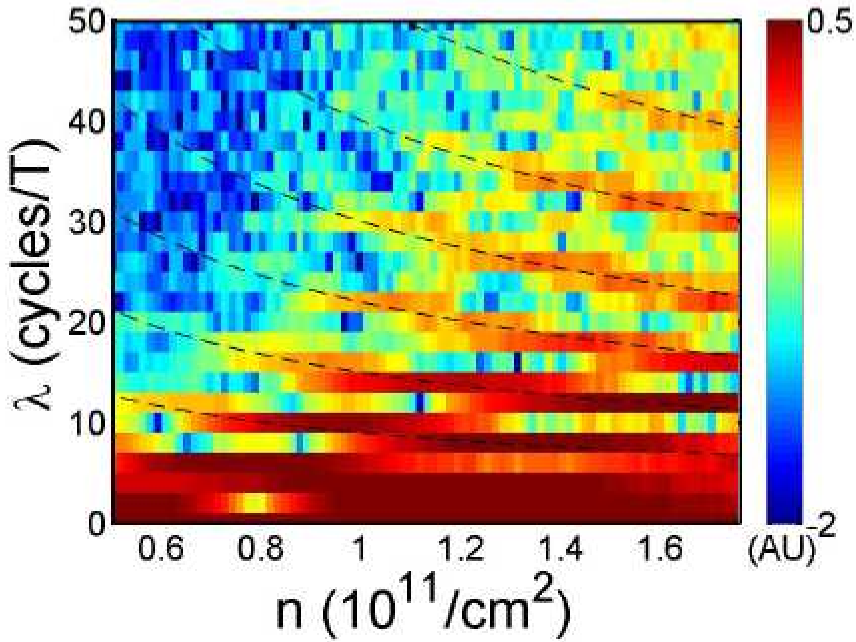




- Array of holes with 110 nm diameter patterned in the gate
- At high density, mobility is only reduced by a factor of ~2

Artificial superlattice





- Observe commensurate and quantum oscillations in the magneto resistance as a function of density
- Can be fitted to extract *in-situ* potential parameters
- Could be used to create artificial graphene

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Summary

- Capacitively induced 2DEG in shallow Si/SiGe heterostructures
  - Can get ~ 3 x 10^5 cm^{-2} / V ·s in 25 nm shallow devices
  - Non-equilibrium charge migration model enhances mobility at high density
- Capacitively induced 2DHG in Ge/SiGe heterostructures
  - Lowest achieved density of ~ 1.5 x 10^{10} cm^{-2}
  - charge migration model important to describe scattering mechanisms at higher density
  - Larger effective hole mass than expected from doped systems
- More involved possibilities with Si/SiGe heterostructures
  - Electron bilayer
  - Artificial disorder/superlattice

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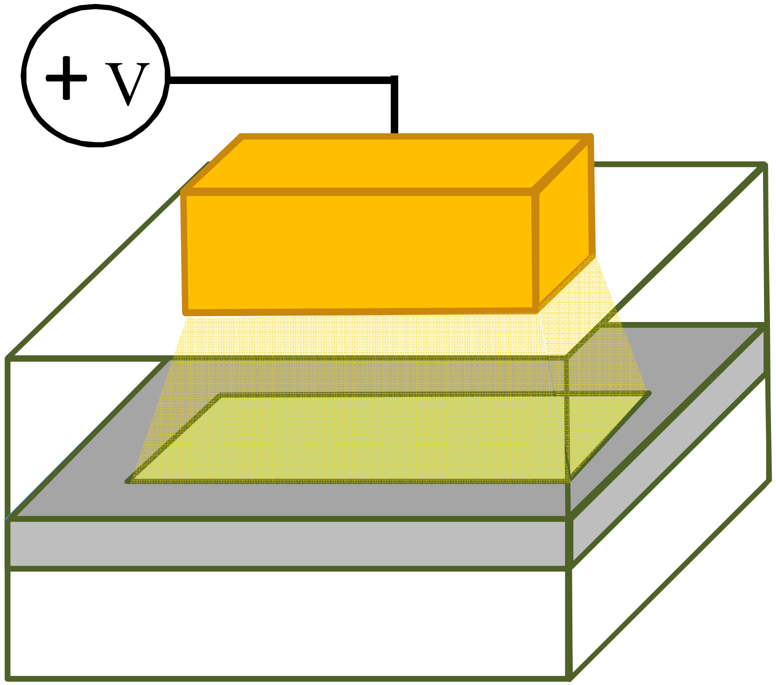
Thank you!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