Quantum phenomena of 2D hole gas in compressive strained epitaxial Germanium

Maksym Myronov

E-mail: M.Myronov@warwick.ac.uk

Department of Physics, The University of Warwick, Coventry CV4 7AL, UK

Quantum transport in 2D systems Session Workshop II (W2), May 23 - 30, 2015, Luchon, France

Outline

High mobility strained Ge and Si QW heterostructures

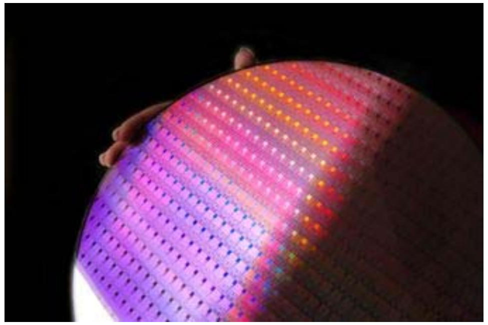
- Carrier mobility
- Epitaxy

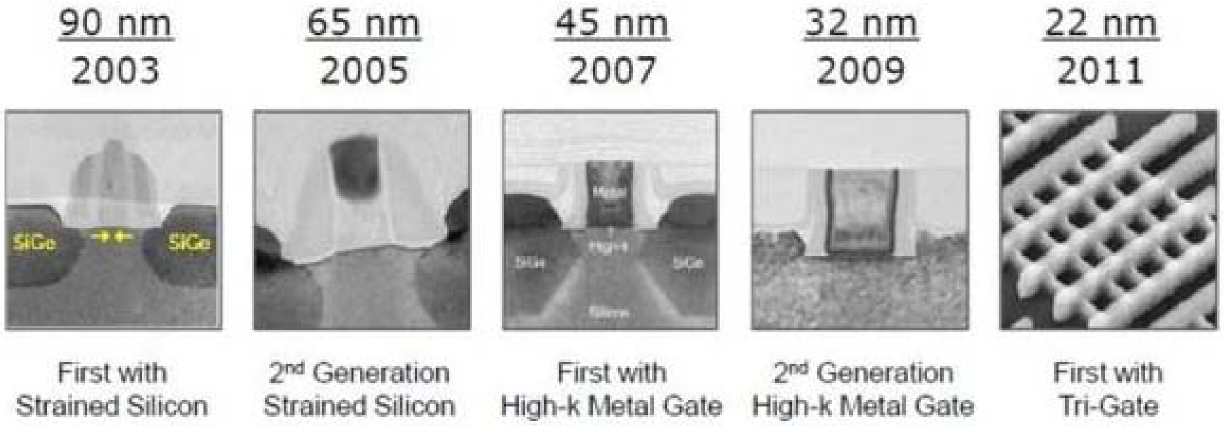
Spin Orbit interaction

- Background
- Weak Localization and Weak Anti-Localisation
- Shubnikov-de Haas effect
- Materials properties
- Detection of spin-orbit interaction

Carrier mobility

Mobility of semiconductor materials

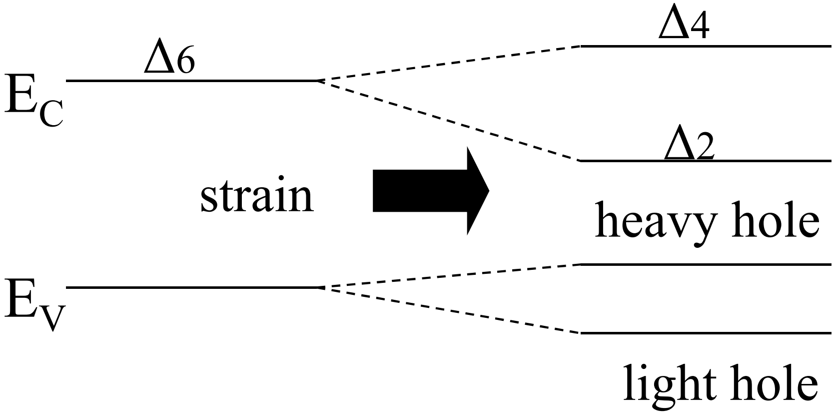


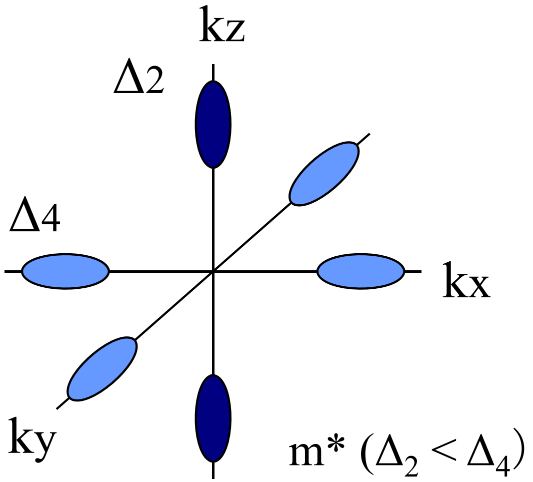


90 nm 2003	65 nm 2005	45 nm 2007	32 nm 2009	22 nm 2011
First with Strained Silicon	2nd Generation Strained Silicon	First with High-k Metal Gate	2nd Generation High-k Metal Gate	First with Tri-Gate

	Si	**Ge**	**3C-SiC**	**GaAs**	**InP**	**InAs**	**InSb**
μ_e (cm^2/Vs)	1450	3900	800	9200	5400	40000	**77000**
m^*_e (m_0)	1.08	0.55	0.68	0.067	0.073	0.027	0.013
μ_h (cm^2/Vs)	480	**1900**	320	400	200	500	850
m^*_h (m_0)	$m^*_{hh}=0.49$ $m^*_{lh}=0.16$	$m^*_{hh}=0.28$ $m^*_{lh}=0.044$	$m^*_{hh}=0.45$ $m^*_{lh}=0.275$	$m^*_{hh}=0.49$ $m^*_{lh}=0.16$	$m^*_{hh}=0.45$ $m^*_{lh}=0.082$	$m^*_{hh}=0.57$ $m^*_{lh}=0.35$	$m^*_{hh}=0.44$ $m^*_{lh}=0.016$
E_G (eV)	1.12 (I)	0.66 (I)	2.36(I)	1.42 (D)	1.34 (D)	0.36 (D)	0.17 (D)

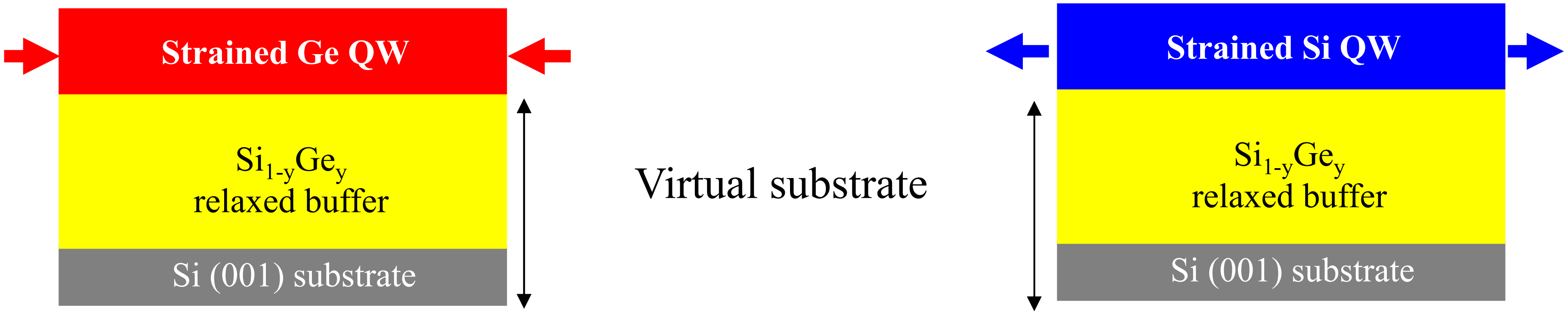
Strain changes structural, electronic and optical properties of an elementary material





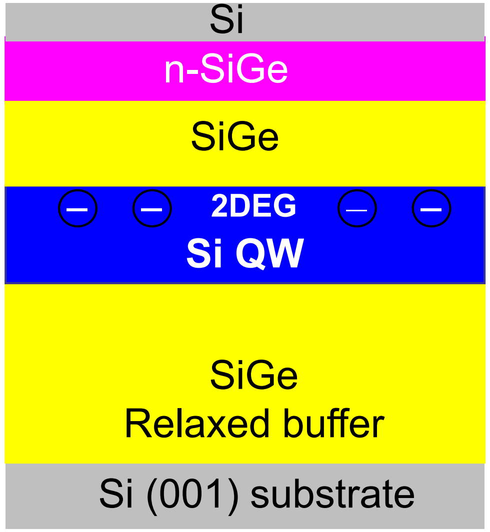
- effective mass decreases
- inter-valley scattering decreases

Mobility of electrons and holes increases



SiGe modulation doped heterostructures (MODH)

2DEG MODH

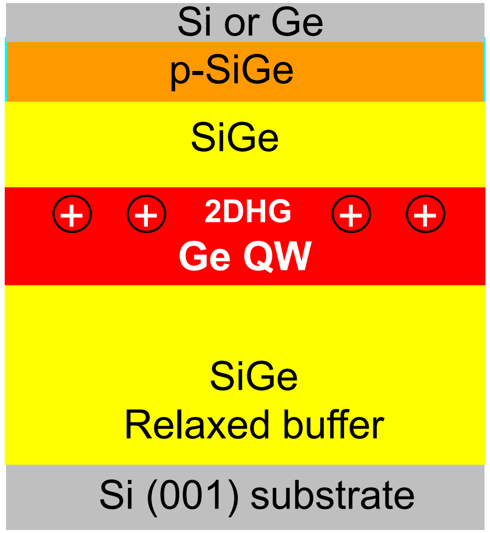


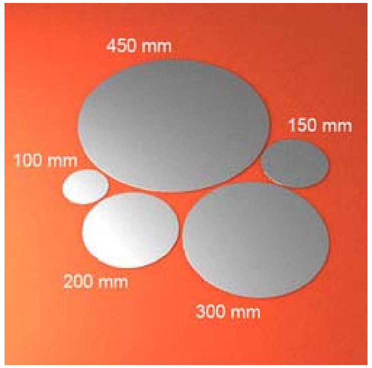
Cap
Doping
Spacer

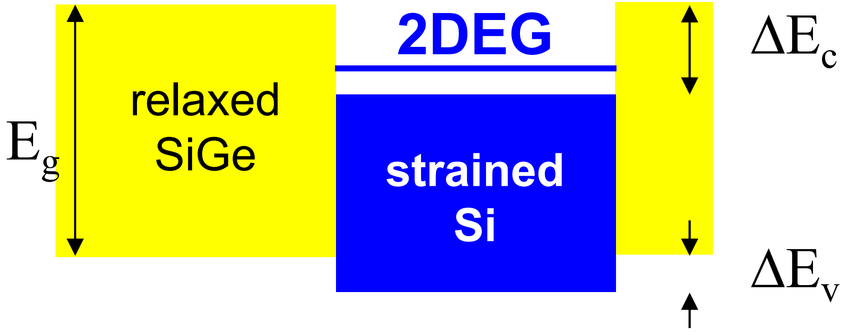
QW or channel

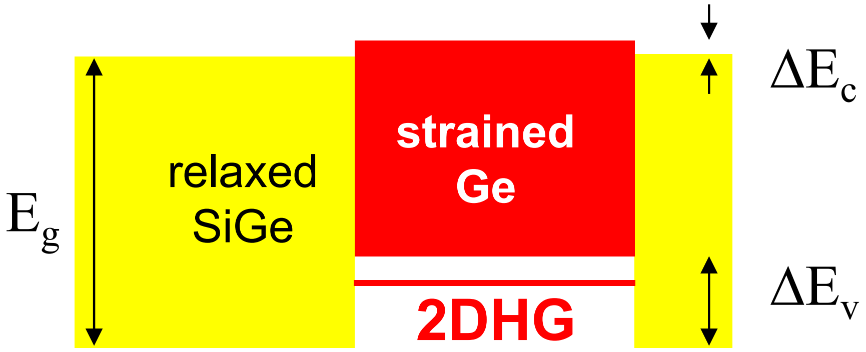
Buffer

2DHG MODH

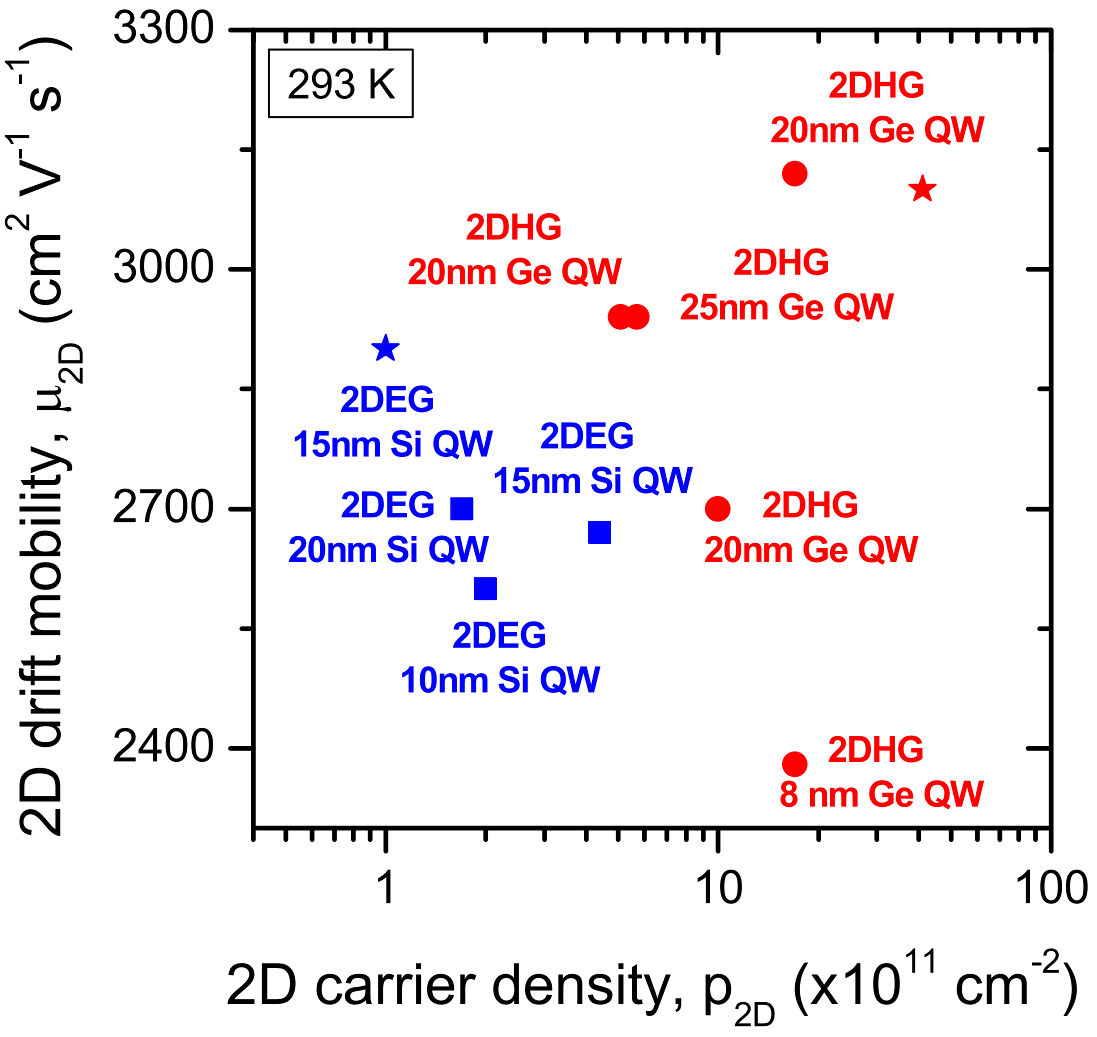


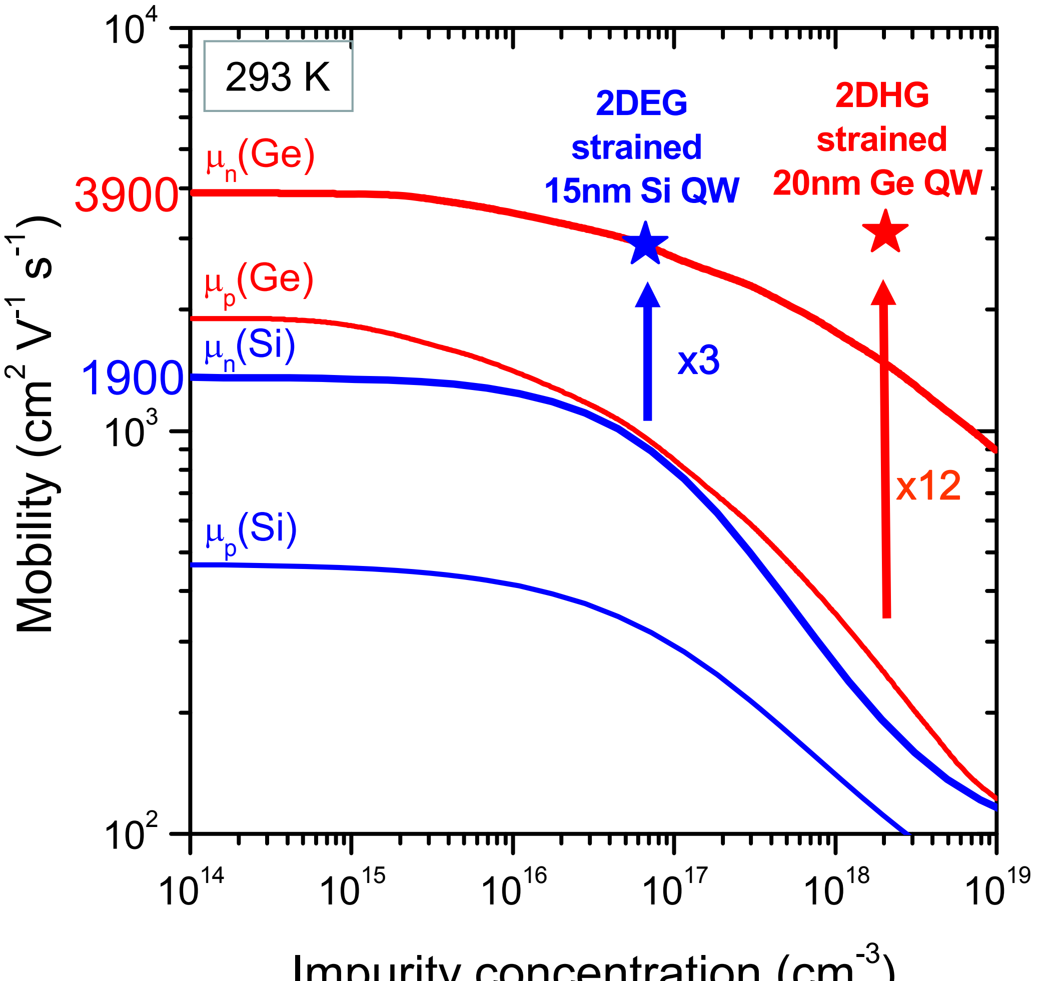






High mobility 2DHG and 2DEG in strained Ge and Si QWs by 2011

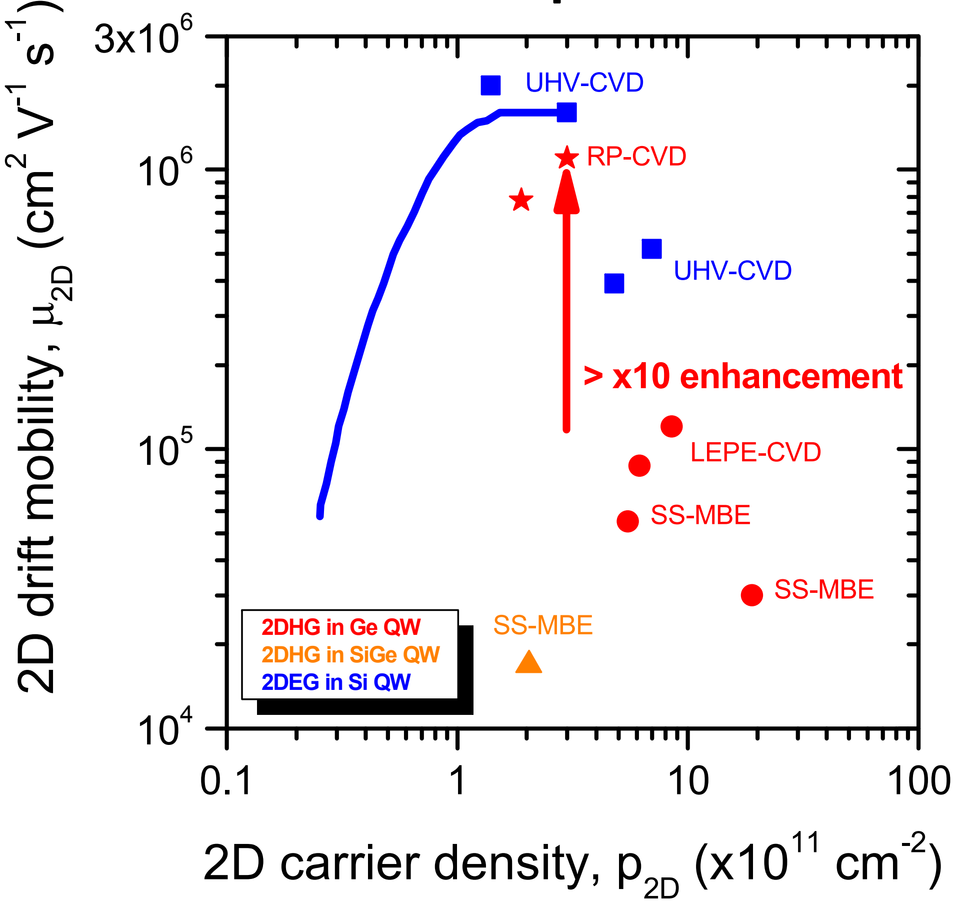




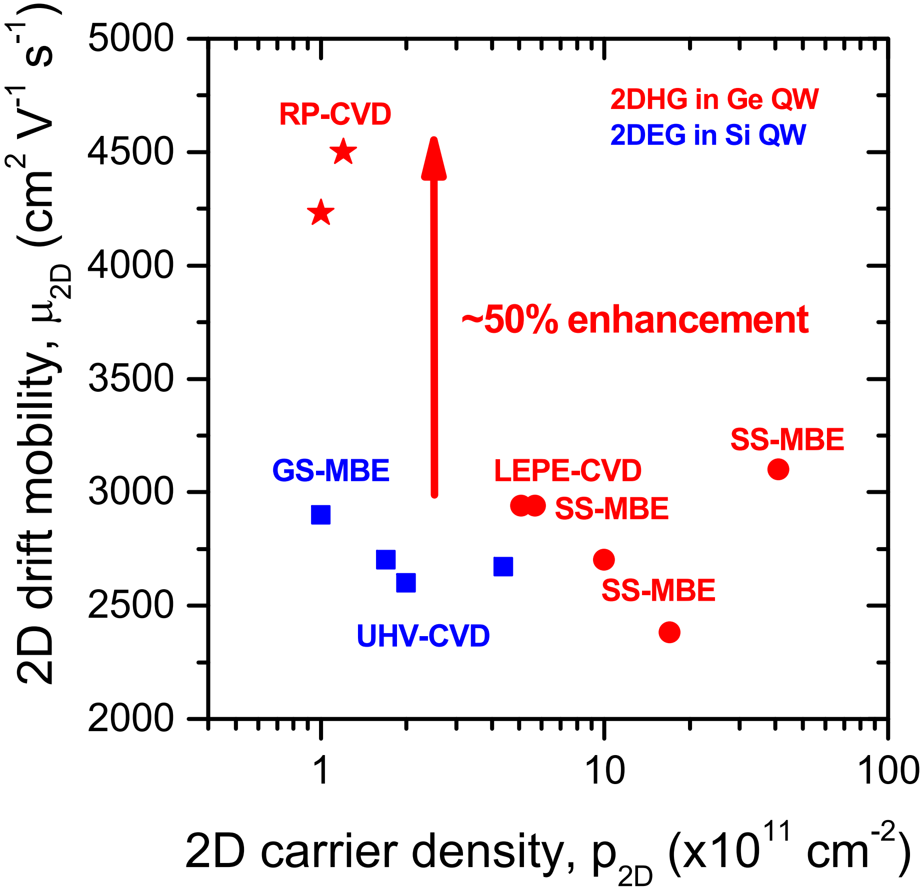
★ *M. Myronov et al* Applied Physics Letters **91**, 082108 (2007)
★ *M. Myronov et al* Applied Physics Express **1**, 021402 (2008)

The highest 2DHG and 2DEG mobilities in strained Ge and Si QWs

Low-temperatures



Room-temperature



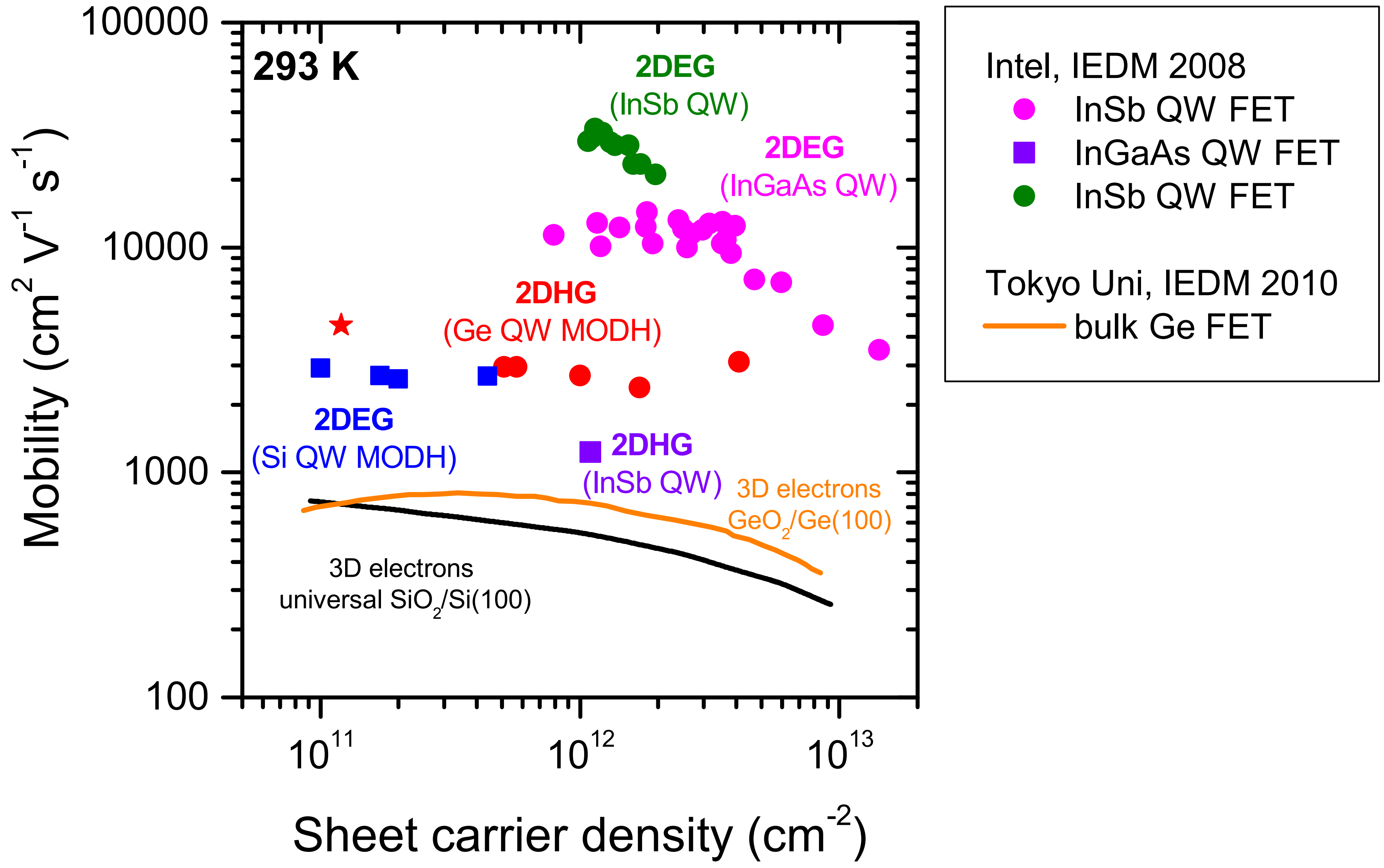
2DEG in strained Si QW demonstrates
higher mobility than
2DHG in strained Ge QW

2DHG in strained Ge QW demonstrates
higher mobility and carrier density than
2DEG in strained Si QW

★ *M. Myronov et al* Solid-State Electronics **110**(0): 35-39 (2015).

★ *A. Dobbie, M. Myronov et al* Applied Physics Letters **101**(17) 172108 (2012).

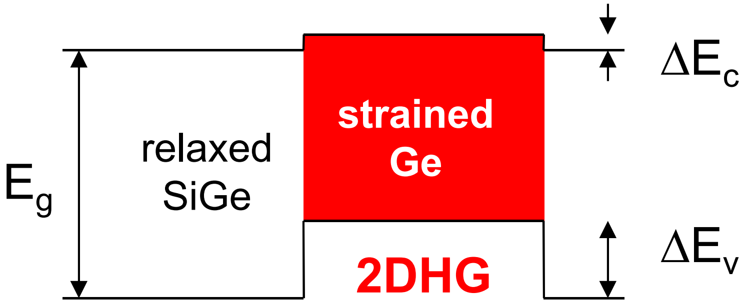
Comparison of group IV and III-V materials performance for application as an FET channel



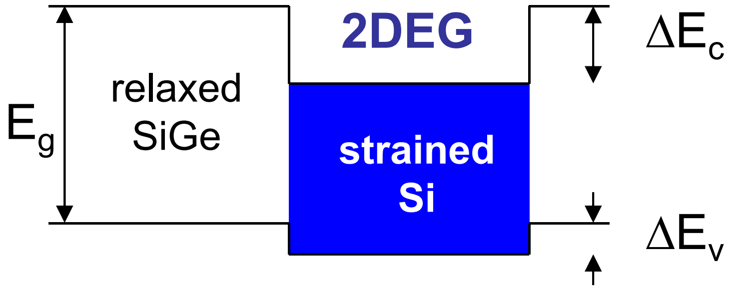
★ *M. Myronov et al* Solid-State Electronics **110**(0): 35-39 (2015).

Carrier mobility

p-type Ge QW heterostructure



n-type Si QW heterostructure



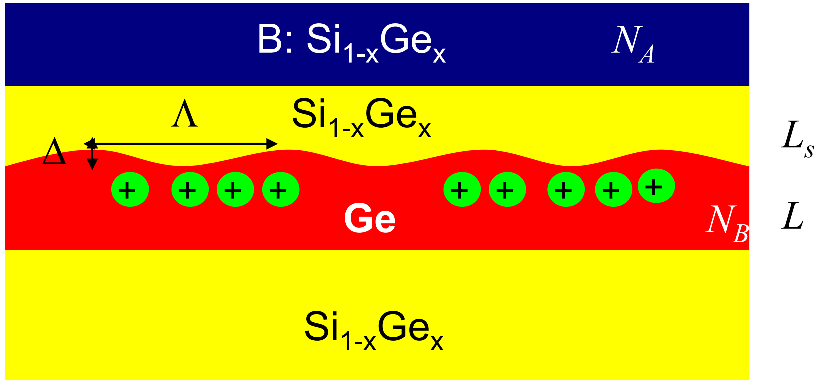
$$\mu = \frac{e \cdot \tau}{m^*}, \qquad \frac{1}{\tau} = \sum_i \frac{1}{\tau_i} \qquad \frac{1}{\mu} = \sum_i \frac{1}{\mu_i}$$

T = 4 K

$$\mu = \frac{e}{4 \cdot \pi \cdot \hbar^2 \cdot p_s \cdot k_B \cdot T} \cdot \int_0^\infty \frac{E \cdot \tau(E) dE}{\cosh\left(\frac{E - \zeta}{2 \cdot k_B \cdot T}\right)}$$

T = 293 K

Carrier scattering mechanisms affecting 2DHG mobility in a Ge QW



T = 4 K

Interface-roughness scattering

$$\mu_{IR} \propto p_s^{1.5} \cdot L^6 \cdot \Lambda^3 / \Delta^2$$

Background ionized impurity scattering

$$\mu_{BI} \propto 1 / N_B \cdot L$$

Remote ionized impurity scattering

$$\mu_{RI} \propto p_s^{1.5} \cdot L_s^3 / N_A$$

Dislocations scattering

$$\mu_D \propto 1/TDD$$

$$\mu_D = 20{,}000{,}000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \text{ at TDD} = 10^6 \text{ cm}^{-2}$$

Don Monroe et al J. Vac. Sci. Technol. B **11** p.1713 (1993)

T = 293 K

Interface-roughness scattering

$$\mu_{IR} \propto p_s^{1.5} \cdot L^6 \cdot \Lambda^3 / \Delta^2$$

Background ionized impurity scattering

$$\mu_{BI} \propto 1 / N_B \cdot L$$

Remote ionized impurity scattering

$$\mu_{RI} \propto p_s^{1.5} \cdot L_s^3 / N_A$$

Dislocations scattering

$$\mu_D \propto 1/TDD$$

Acoustic and optical phonons scattering

$$\mu_{AP} \propto L, \ \mu_{OP} \propto L$$

Epitaxy

Group IV semiconductors epitaxial growth techniques

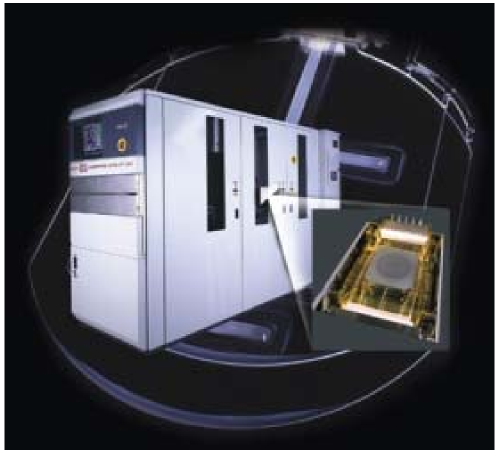
Molecular Beam Epitaxy (MBE)

Solid-Source Molecular Beam Epitaxy (**SS-MBE**)
– **ultimate research tool**

Gas-Source MBE (**GS-MBE**)

Chemical Vapour Deposition CVD

Ultra High Vacuum Chemical Vapour Deposition (**UHV-CVD**)

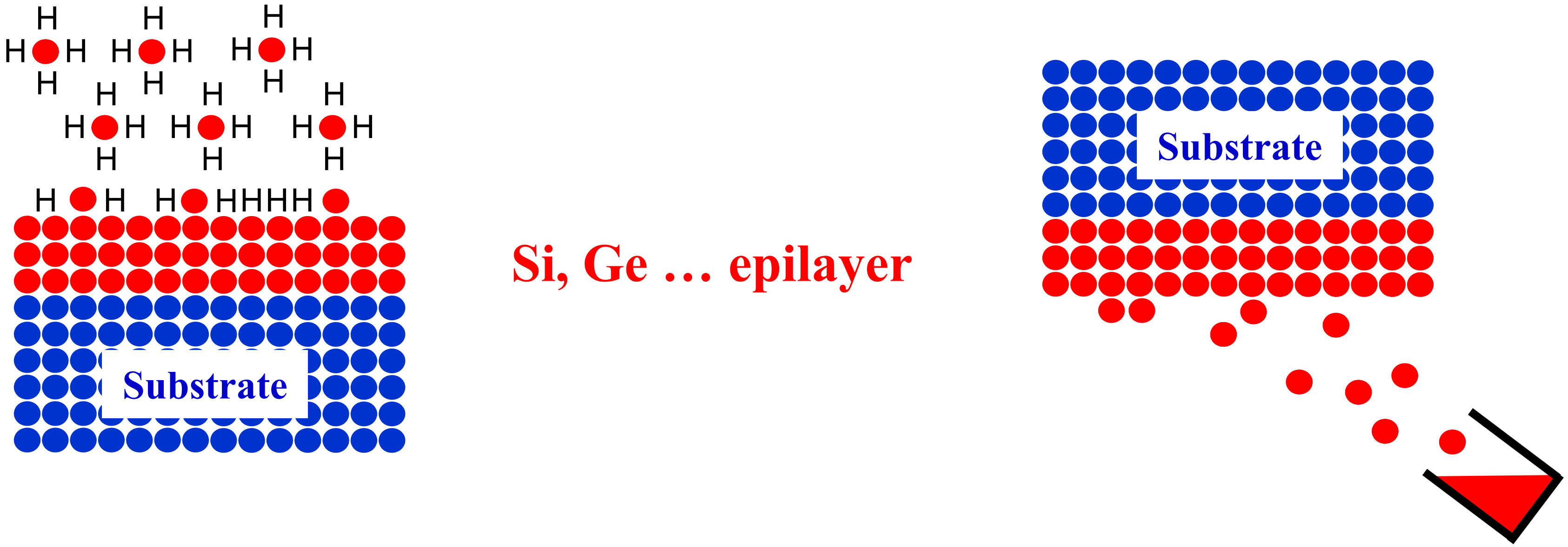


Low Energy Plasma Enhanced CVD (**LEPE-CVD**)

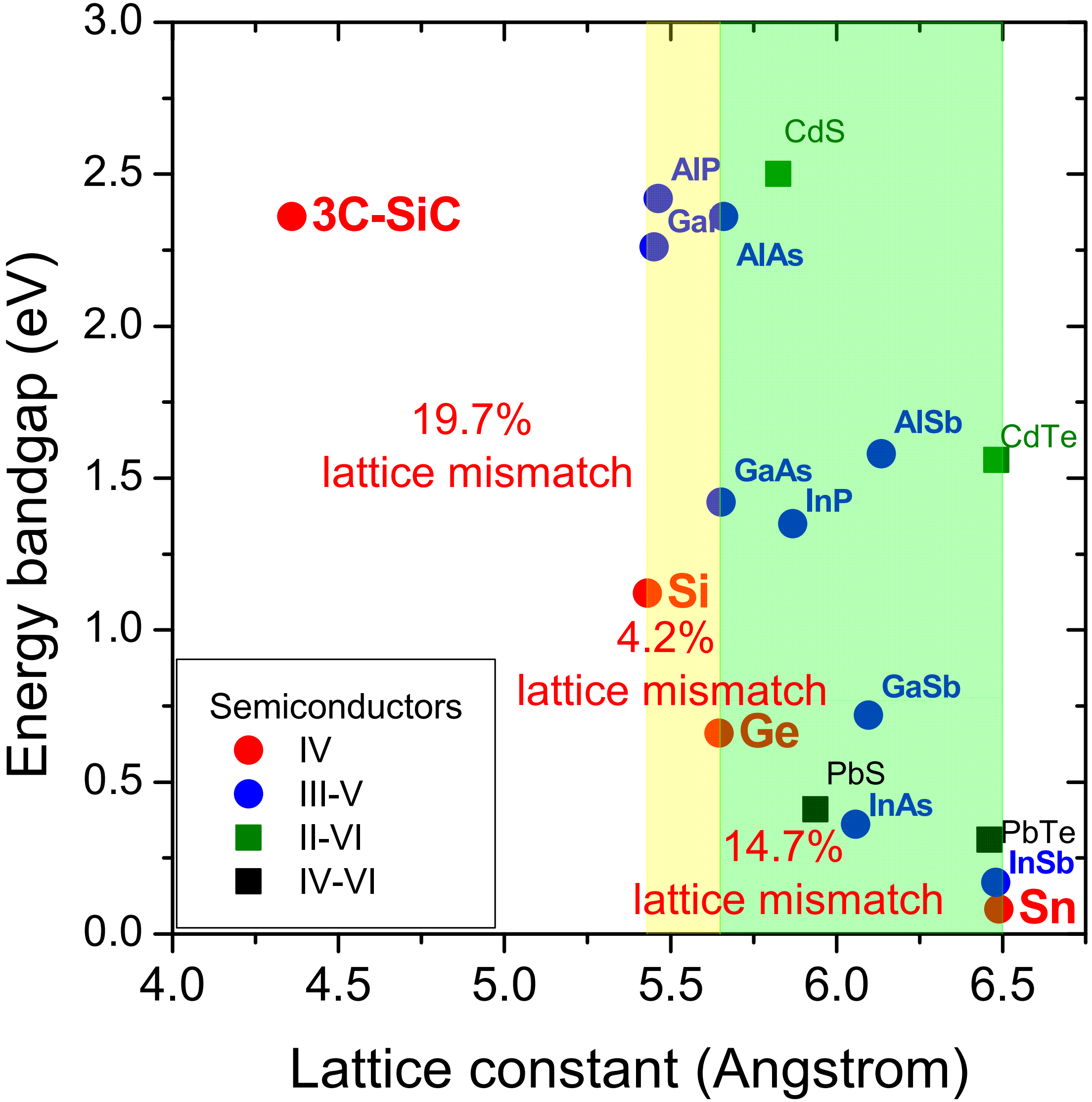
Reduced Pressure (**RP-CVD**)
– **ultimate industrial tool**

Difference in growth by CVD and MBE

Chemical Vapour Deposition | **Molecular Beam Epitaxy**



Lattice mismatch strain is an essential parameter for band structure engineering



THE UNIVERSITY OF WARWICK

SiGe critical thickness

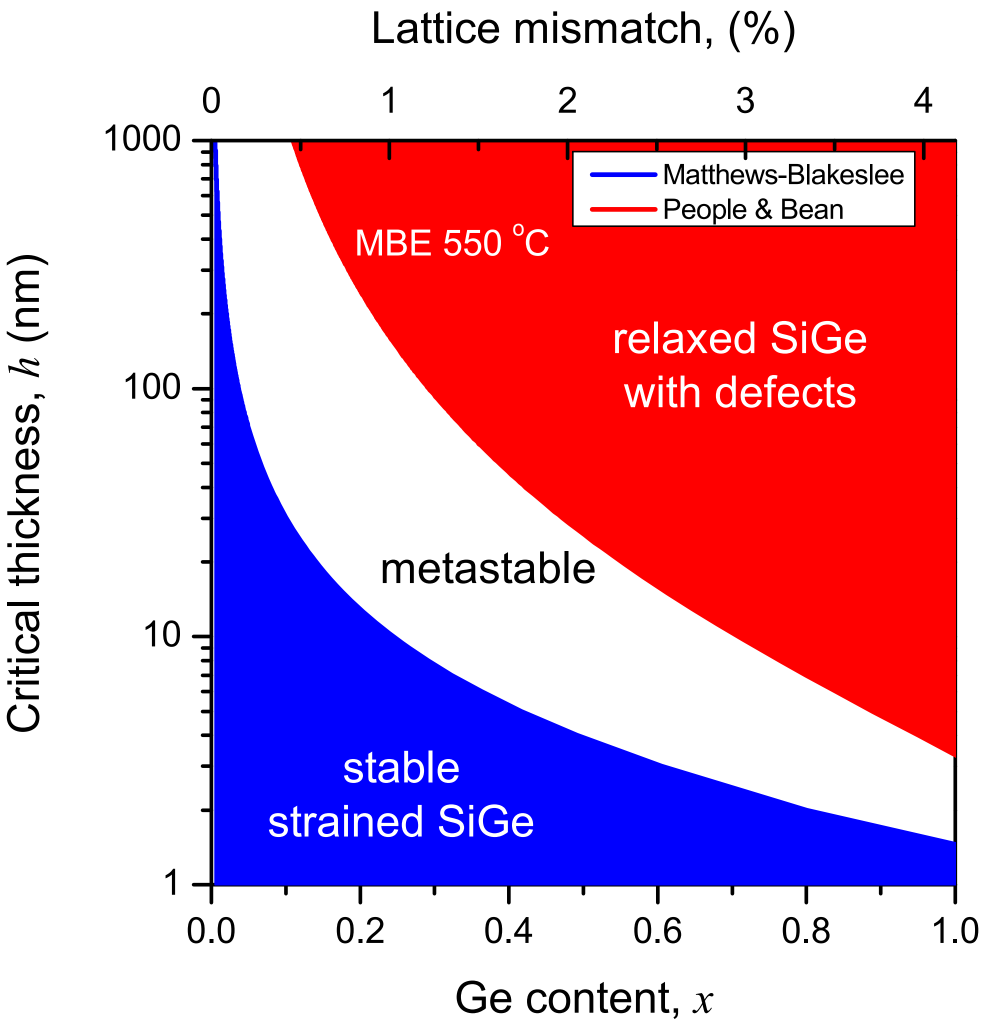
Matthews-Blakeslee - isolated dislocations

$$x = 1.383 \frac{b}{h} \ln\left(\frac{4h}{b}\right)$$

People & Bean - energy balance

$$x = 2.01 \sqrt{\frac{b}{h} \ln\left(\frac{h}{b}\right)}$$

x - Ge concentration
b = 0.38 nm - Burgers vector
h - critical thickness



*J.W. Matthews and A.F. Blakeslee J. Cryst. Growth **27**, 118 (1974)*
*R. People and J.C. Bean Appl. Phys. Lett **47**, 322 (1985)*

Epitaxial growth systems

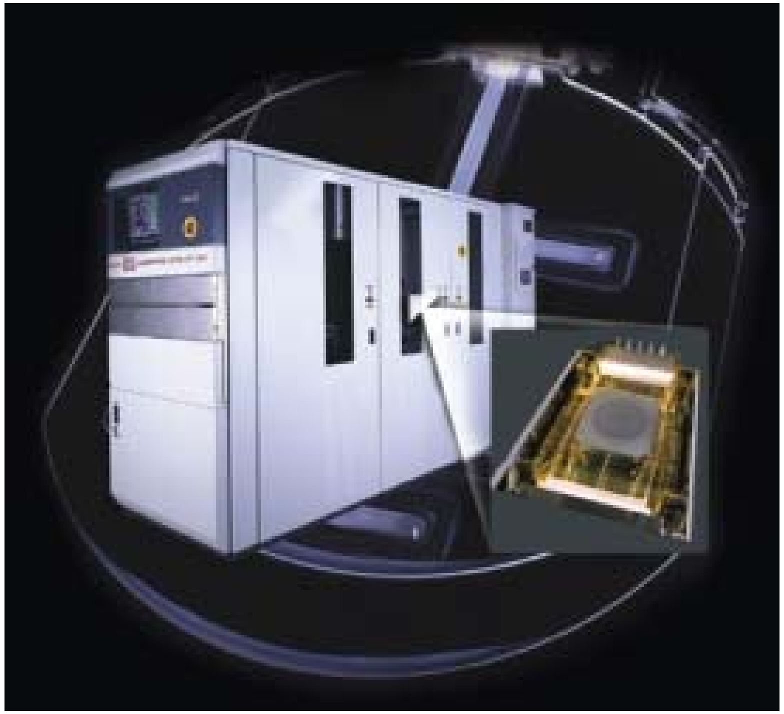
VG Semicon V90S MBE

(since 1995)

Si, Ge, and SiGe epitaxy

ASM Epsilon 2000 CVD

(since 2004/2008)



Si, Ge, SiGe, SiC,

GeSn … epitaxy

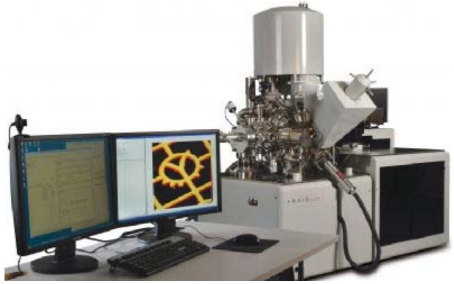
LPE ACIS-M8 CVD

(since 2014)

SiC epitaxy

Comprehensive materials characterization

- •Transmission Electron Microscopy (TEM)
- •X-ray diffraction (XRD) and reflectivity
- •Atomic Force Microscopy (AFM)
- •Scanning Electron Microscopy (SEM)
- •Defects revealing
- •Secondary Ion Mass Spectrometry (SIMS)
- •X-ray Photoelectron Spectroscopy (XPS)
- •Spectroscopic ellipsometry (SE)
- •Fourier Transform Infrared Spectroscopy (FTIR)
- •Raman spectroscopy
- •Photoluminescence
- •Total Reflection X-ray Fluorescence (TXRF)
- •…



- •Resistivity and Hall effect measurements (0.3-300 K)
- •Magnetotransport (0.3 - 300 K, up to 12 T)
- •Electrochemical C-V (eC-V)
- •Mercury probe C-V
- •Current–voltage (10 – 300 K)
- •Conductance–voltage (10 – 300 K)
- •Capacitance–voltage (10 – 300 K)
- •4 Point Probe resistivity (4PP)
- •Deep Level Transient Spectroscopy (DLTS)
- •….

Quantum phenomena in strained Ge QW heterostructures

- Integral Quantum Hall effect
- Fractional Quantum Hall effect
- **Shubnikov de-Haas effect**
- **Weak localization**
- **Weak anti-localization**
- Stark effect

…

Spin-orbit interaction

Spintronics

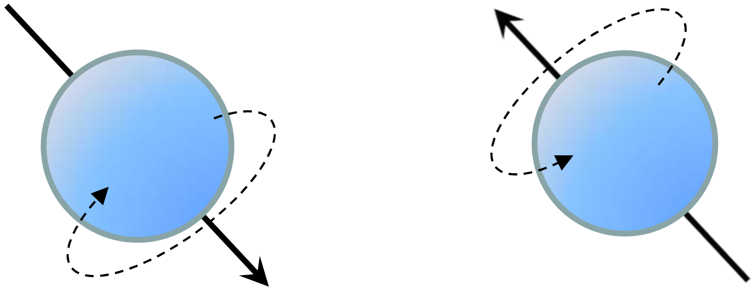
- Electrons have ½ spin which can be either up or down.

- It is this spin which causes electrons to produce a magnetic moment.

$$\vec{\mu} = \frac{ge\vec{s}}{2m} = \frac{e\hbar}{2m}$$

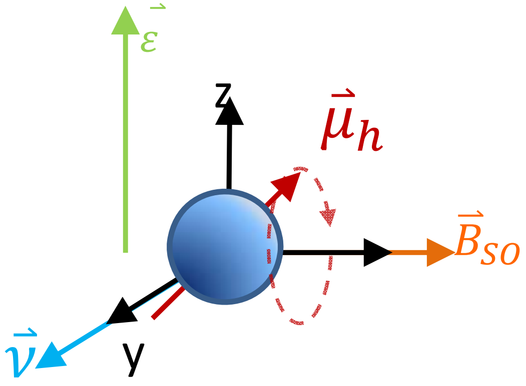
- **Spintronics is a branch of electronics where electron or hole transport is dominantly spin dependent.**

- Spintronics promises lower energy consumption compared to regular electronics:
  - Charge interaction energy scale: eV
  - Spin interaction energy scale: meV



Spin-Orbit (SO) interaction

- The spin-orbit (SO) interaction is a relativistic effect in which an electron experiences an electric field as an effective magnetic field.
- In an isolated atom the electric field arises from the positively charged nucleus.
- Conduction electrons do not experience a strong SO interaction with nuclei, but do experience an effective magnetic field from other sources of electric fields:
  - **Dresselhauss interaction**: arises from bulk inversion asymmetry. (Not seen in group IV materials)
  - **Rashba interaction:** arises from external electric fields or built in potentials such as quantum wells.



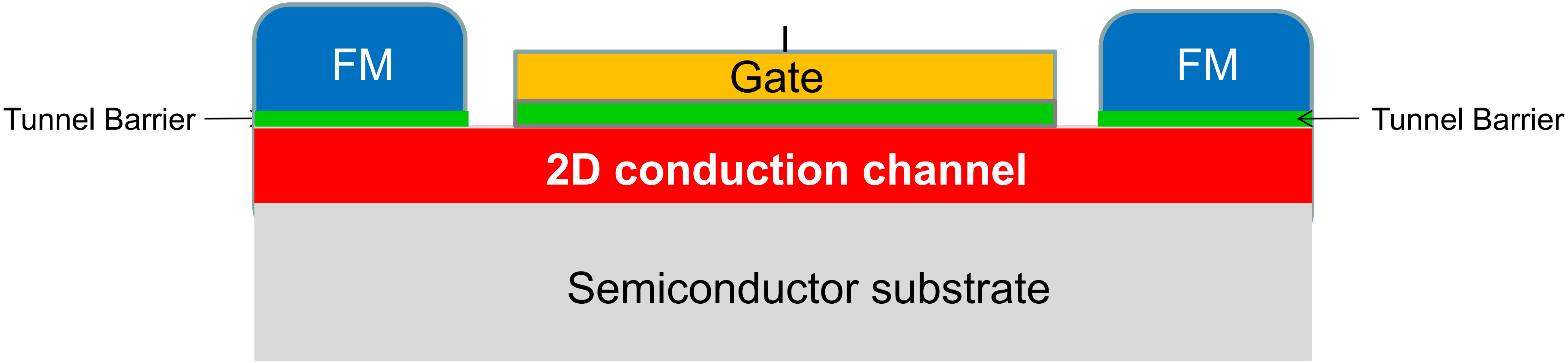
Why is the SO interaction relevant to spintronics?

- SO interaction is a source of spin relaxation as the effective magnetic field which is momentum dependent causes the spins to precess and supress spin polarisation (Dyakonov-Perel relaxation).

- The Rashba SO interaction can be used to modulate spins simply by applying an electric field to intentionally induce Larmor precession. A prime use of this effect is the spin field effect transistor.

Spin-FET

- The spin-FET was proposed in 1990 by S. Datta and B. Das.
- Consists of two spin tunnel contacts used to inject and extract spin, separated by a gated 2D conduction channel/quantum well
- The separation of the contacts must be smaller than the spin relaxation length.
- The ferromagnetic contacts will have parallel or anti parallel magnetisation.



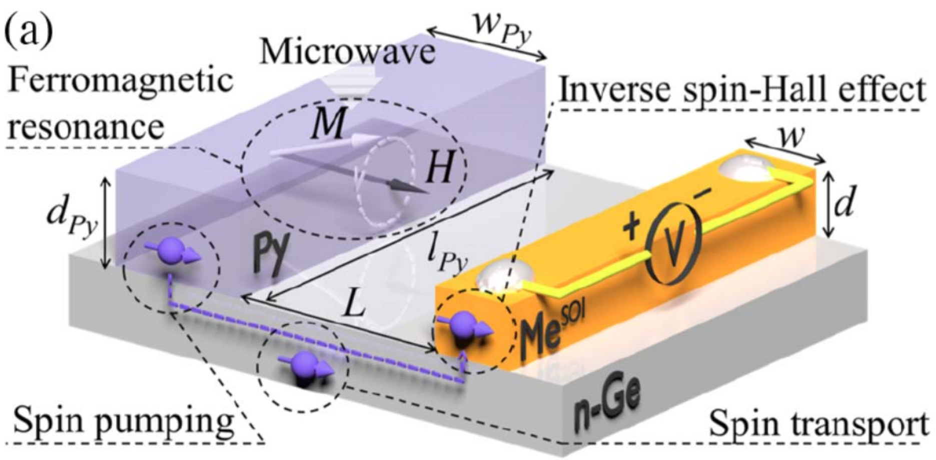
S. Datta and B. Das “Electronic analog of the electro-optic modulator." Applied Physics Letters **56**(7): 665-667 (1990).

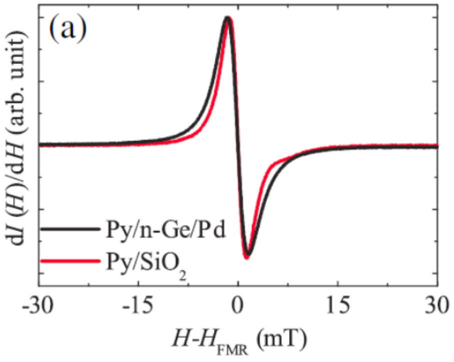
Germanium spintronics

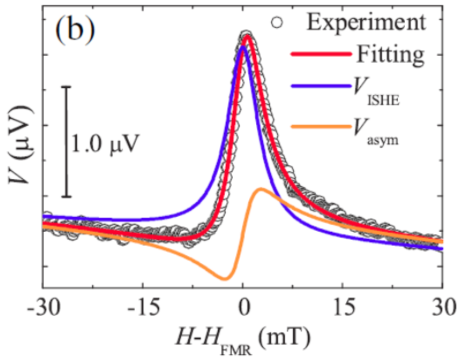
Ge is a promising platform for semiconductor spintronics, with various advantages over Si and III-V materials:

- High hole mobility for long spin relaxation lengths
- Higher spin orbit (SO) interaction than Si needed for spin modulation
- Absence of Dresselhaus interaction, an untunable SO interaction originating from bulk inversion asymmetry and a main source of spin relaxation in III-V materials
- Highly compatible with Si technology and existing infrastructure

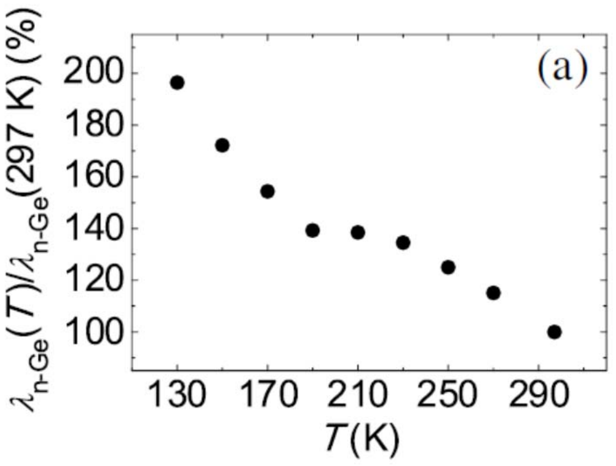
Experimental demonstration of room-remperature spin transport in n-type Germanium epilayers



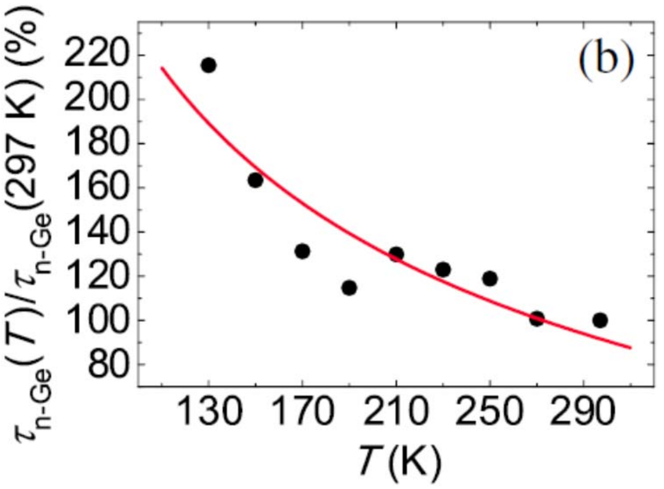




Spin diffusion length



Spin relaxation time



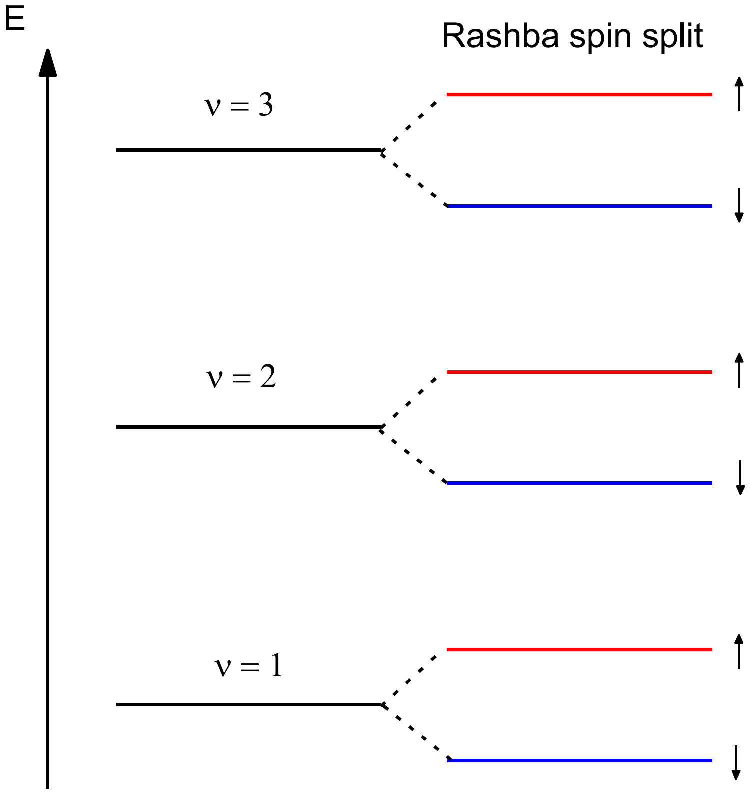
S. Dushenko, M. Koike, Y. Ando, T. Shinjo, M. Myronov, and M. Shiraishi Physical Review Letters 114, 196602 (2015)

Rashba interaction and Shubnikov-de Haas effect

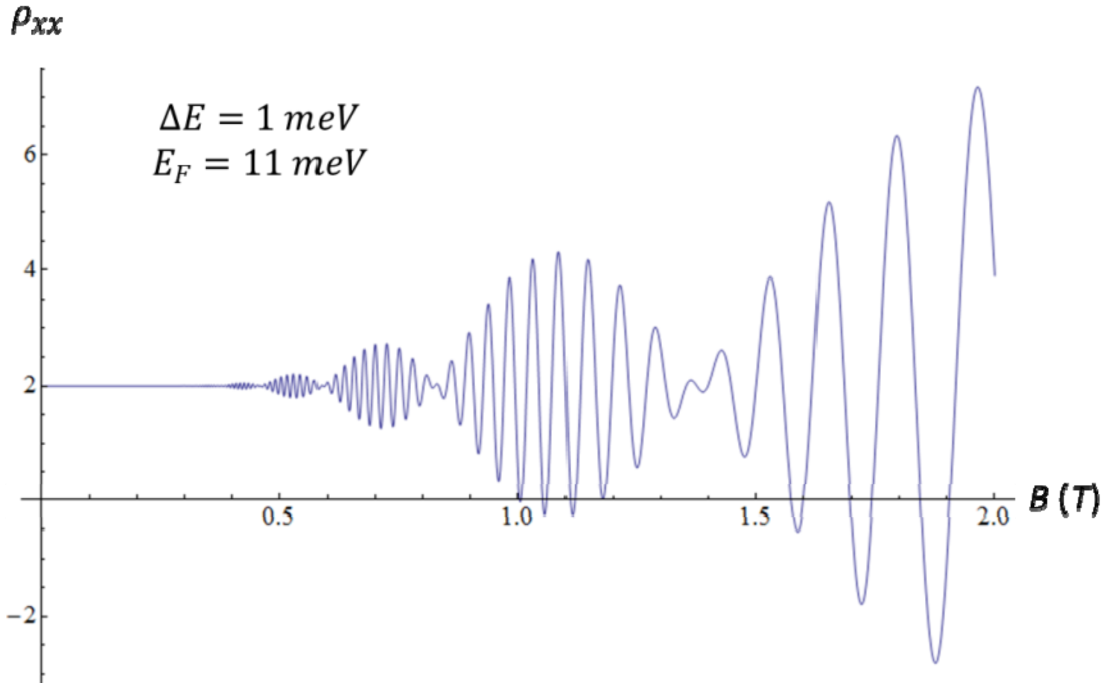
- Shubnikov-de Haas oscillations occur in the resistance of a semiconductor due to energy level creation (Landau levels) in an applied magnetic field.

- These levels can be split by the extra energy from the Rashba interaction into two levels, one for spin up and one for spin down carriers.

- This results in two oscillation frequencies, which interfere with each other to produce a 'beating' pattern of oscillations.



Modelling of Shubnikov-de Haas oscillations of magnetoresistance



Simple model of the oscillation pattern by convolution of two similar oscillation frequencies.

$$\frac{\Delta\rho_{xx}(B)}{\rho_{xx}(0)} = 4\cos\left(\frac{2\pi E_F m^*}{\hbar e B}\right)\exp\left(-\frac{\pi m^* \alpha}{e B \tau_t}\right)\frac{\psi}{\sinh(\psi)}$$

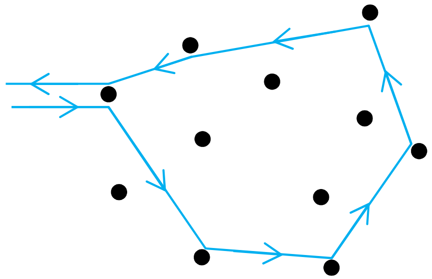
- **Fourier transform allows us to extract the frequencies and calculate the Rashba parameter and the energy of the interaction.**

Weak Localisation (WL)

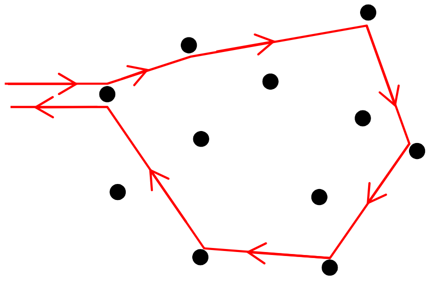
- Weak localization (WL) is a quantum mechanical effect in which the probability of electron backscattering is enhanced, increasing the resistivity of a material above classical values.

- This enhanced probability arises from the propagation of partial electron waves forming closed looped trajectories.

$$\psi = A \cdot e^{i(\vec{k}\vec{r} - \varepsilon(\vec{k})t/h)}$$



$$\psi_1 = A_1 \cdot e^{i\varphi_1}$$



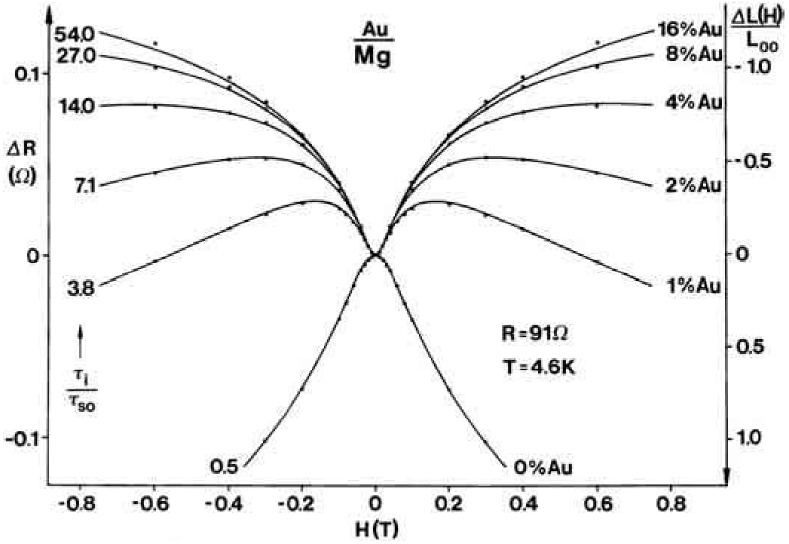
$$\psi_2 = A_2 \cdot e^{i\varphi_2}$$

Weak Anti-Localisation (WAL)

- The SO interaction also provides an additional phase difference (through spin precession) and when strong enough can cause destructive interference giving rise to a reduction of resistivity, this is weak anti-localisation (WAL).

- For WAL to occur the SO scattering length must be smaller than the phase breaking length:

$$L_{SO} < L_{\phi}$$



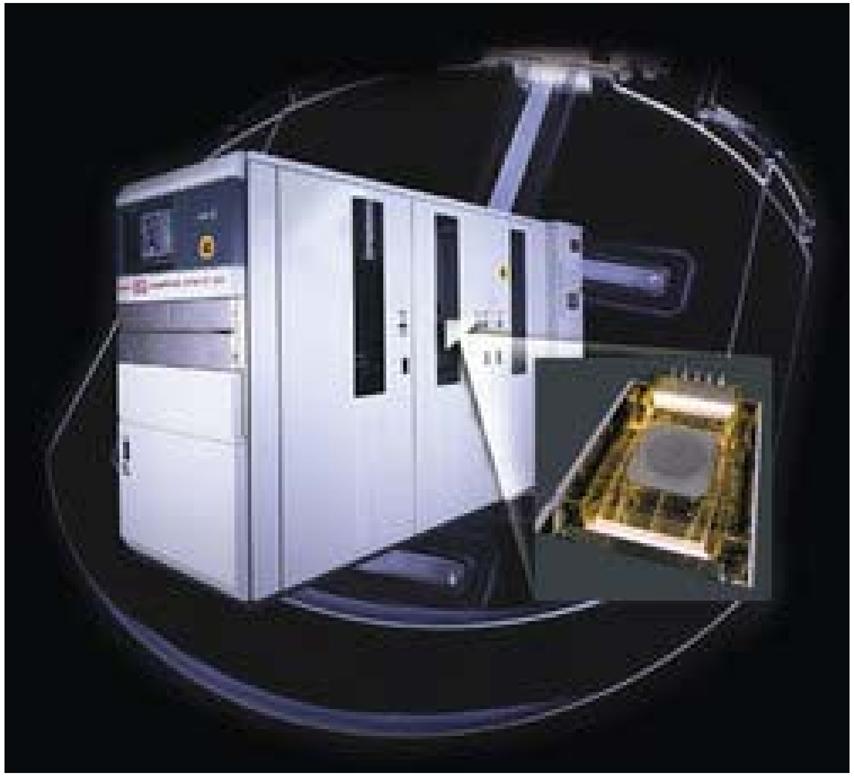
Bergmann, G Phys. Rep. 107, 1 (1984).

- The characteristic shape of WAL in MR curves is a initial positive MR, changing to negative MR at higher fields.

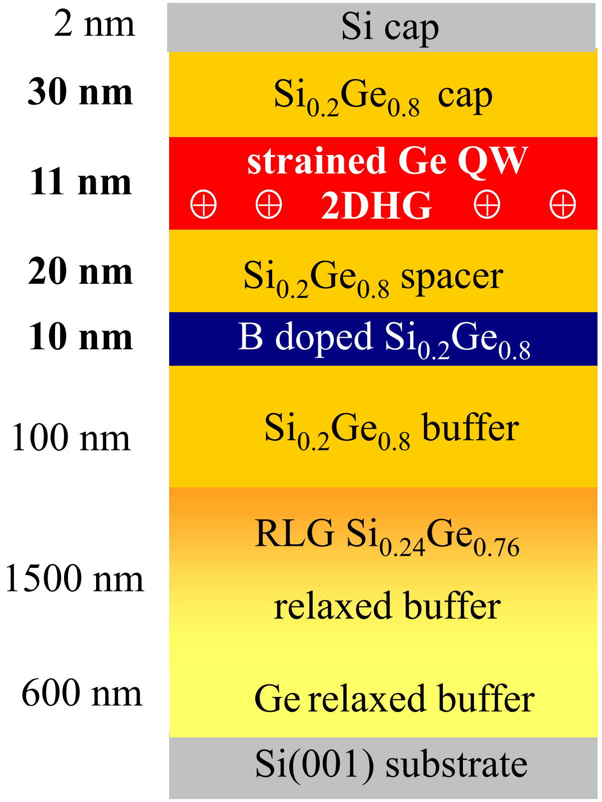
Materials characterization

Epitaxial growth of strained Ge QW MOD heterostructures by RP-CVD

ASM Epsilon 2000 RP-CVD

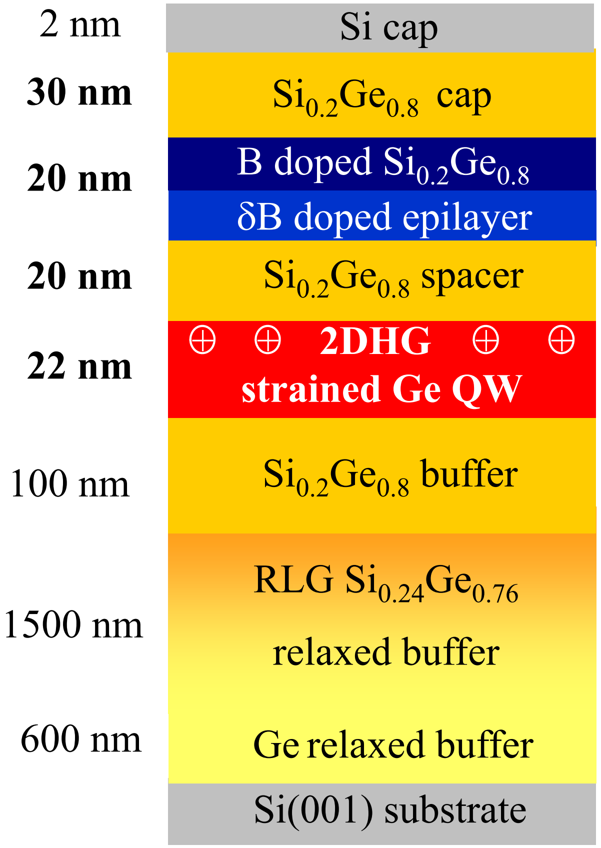


Inverted MOD



2 nm	Si cap
30 nm	$Si_{0.2}Ge_{0.8}$ cap
11 nm	**strained Ge QW** **⊕ ⊕ 2DHG ⊕ ⊕**
20 nm	$Si_{0.2}Ge_{0.8}$ spacer
10 nm	B doped $Si_{0.2}Ge_{0.8}$
100 nm	$Si_{0.2}Ge_{0.8}$ buffer
1500 nm	RLG $Si_{0.24}Ge_{0.76}$ relaxed buffer
600 nm	Ge relaxed buffer
	Si(001) substrate

Normal MOD

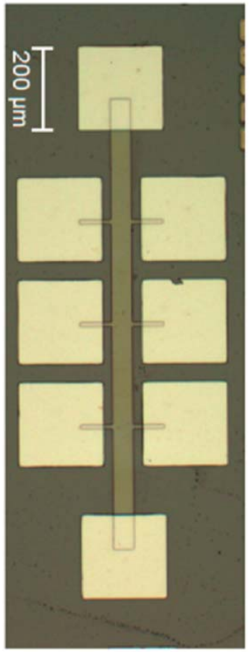


2 nm	Si cap
30 nm	$Si_{0.2}Ge_{0.8}$ cap
20 nm	B doped $Si_{0.2}Ge_{0.8}$ δB doped epilayer
20 nm	$Si_{0.2}Ge_{0.8}$ spacer
22 nm	**⊕ ⊕ 2DHG ⊕ ⊕** **strained Ge QW**
100 nm	$Si_{0.2}Ge_{0.8}$ buffer
1500 nm	RLG $Si_{0.24}Ge_{0.76}$ relaxed buffer
600 nm	Ge relaxed buffer
	Si(001) substrate

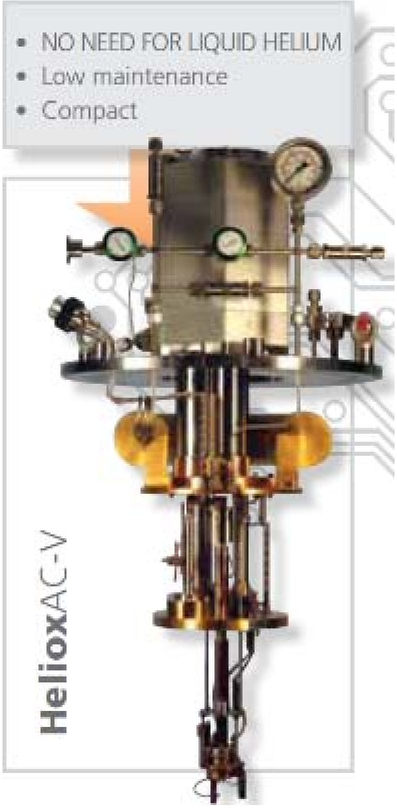
M. Myronov et al Solid-State Electronics **110**(0): 35-39 (2015).
M. Myronov et al Japanese Journal of Applied Physics **53**(4S) 04EH02 (2014).
A. Dobbie, M. Myronov et al Applied Physics Letters **101**(17) 172108 (2012).
M. Myronov et al Electrochemical and Solid-State Letters **13** (11) H388-H390 (2010).
…

Devices fabrication and their characterization

Hall-bar

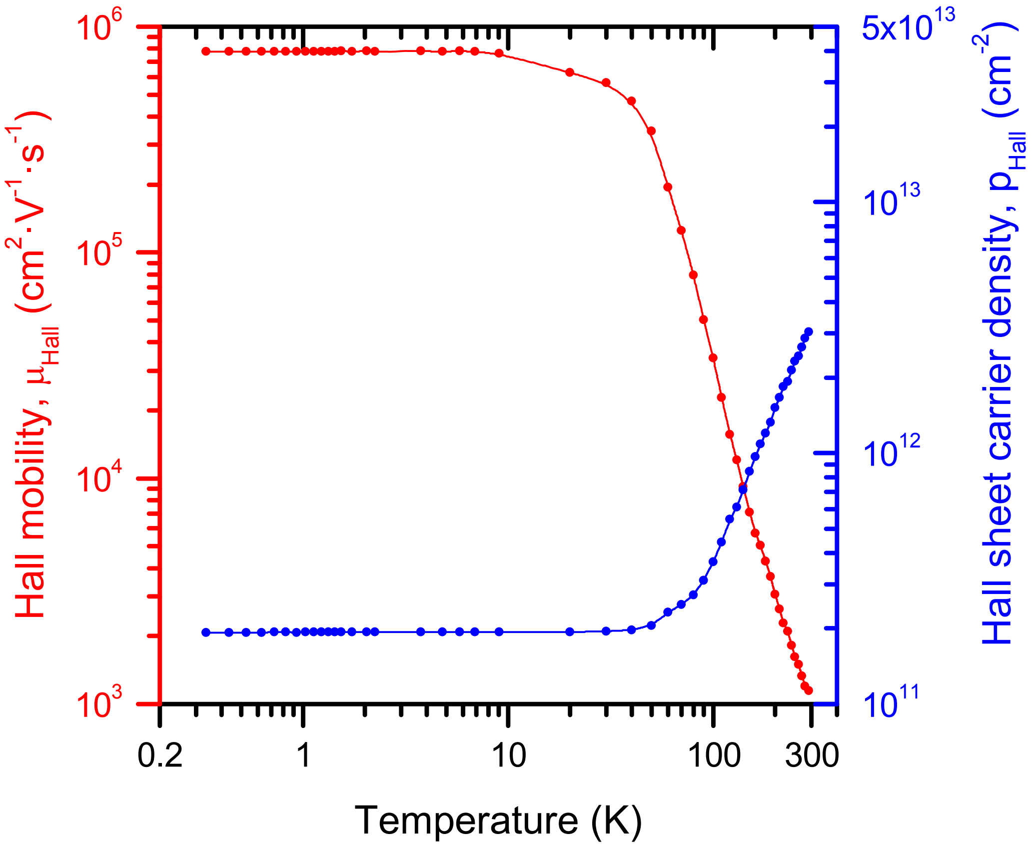


Cryomagnetic system

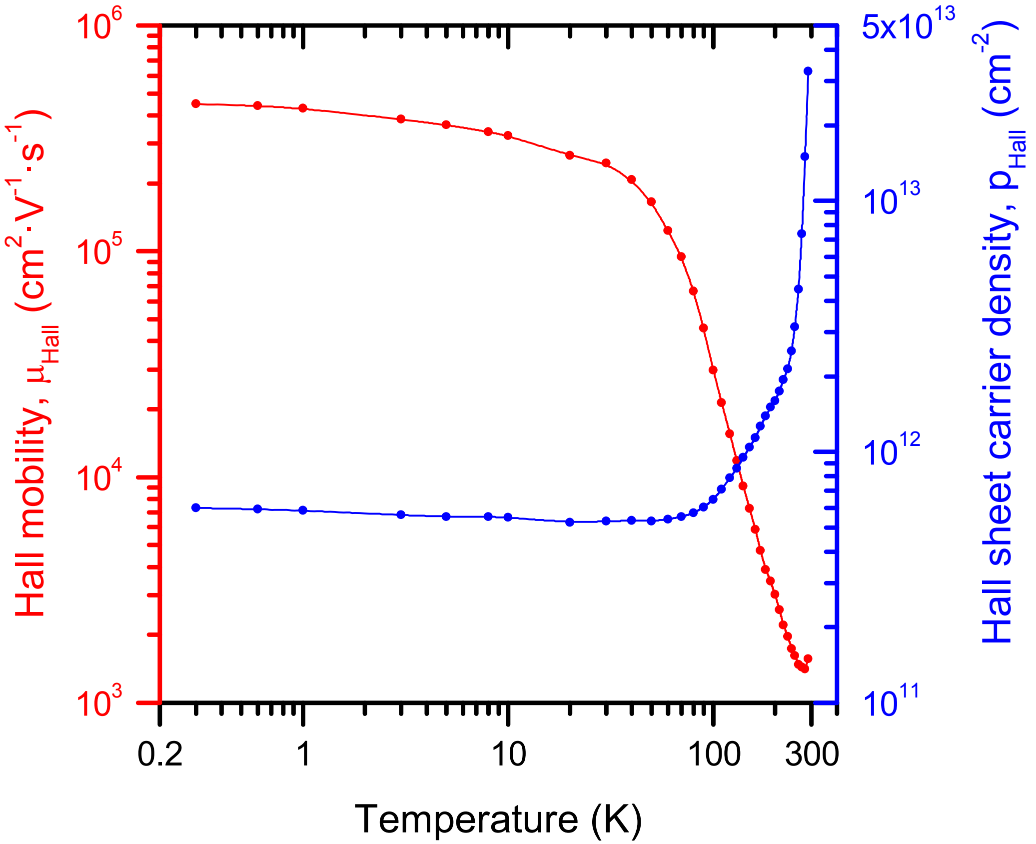

- NO NEED FOR LIQUID HELIUM
- Low maintenance
- Compact

Temperature dependence of Hall mobility and carrier density

Normal MOD



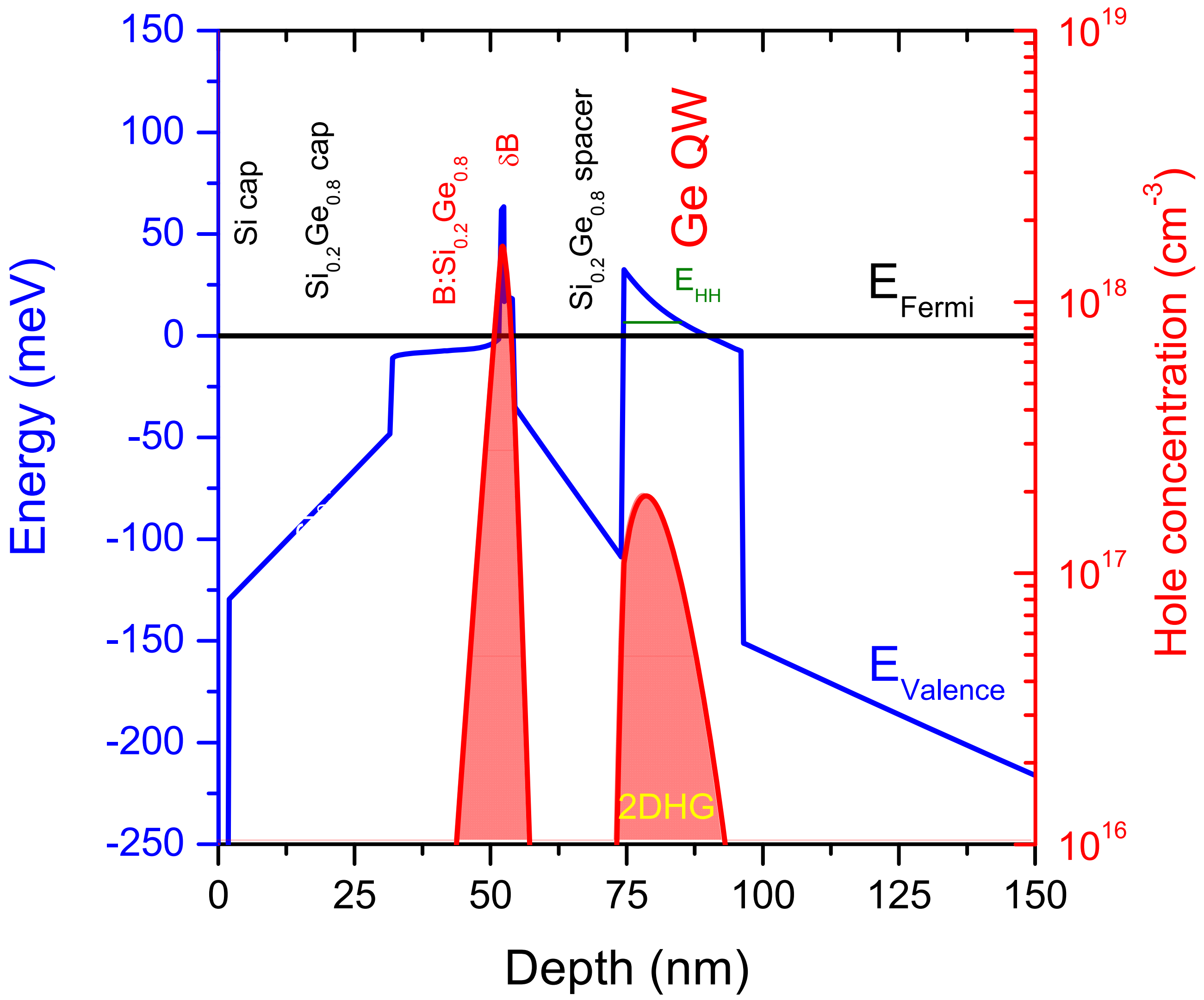
Inverted MOD

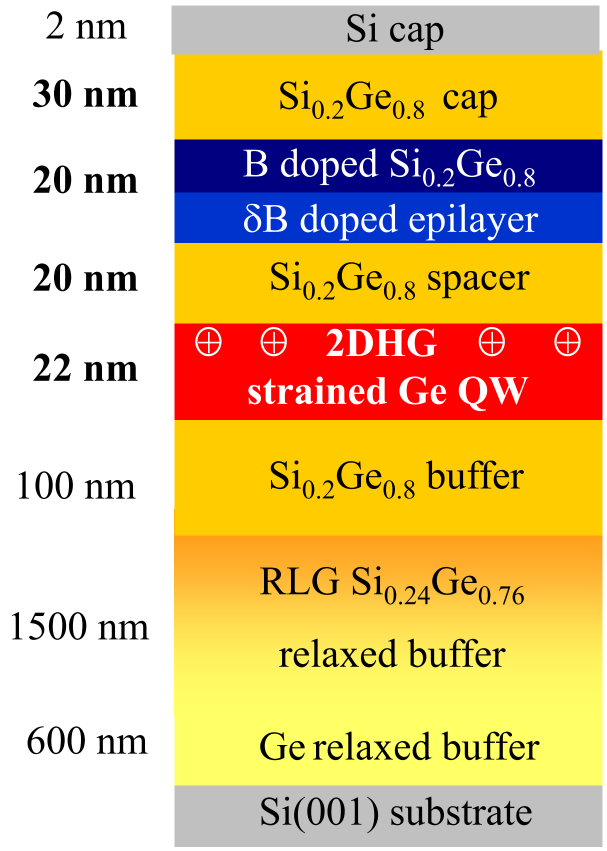


At 0.33 K: $\mu_{\mathrm{Hall}} = 777{,}000\ \mathrm{cm^2V^{-1}s^{-1}}$ at $p_{\mathrm{Hall}} = 1.9\times10^{11}\ \mathrm{cm^{-2}}$

At 0.33 K: $\mu_{\mathrm{Hall}} = 450{,}000\ \mathrm{cm^2V^{-1}s^{-1}}$ at $p_{\mathrm{Hall}} = 5.9\times10^{11}\ \mathrm{cm^{-2}}$

1D self-consistent Schrodinger-Poisson simulation at 4K



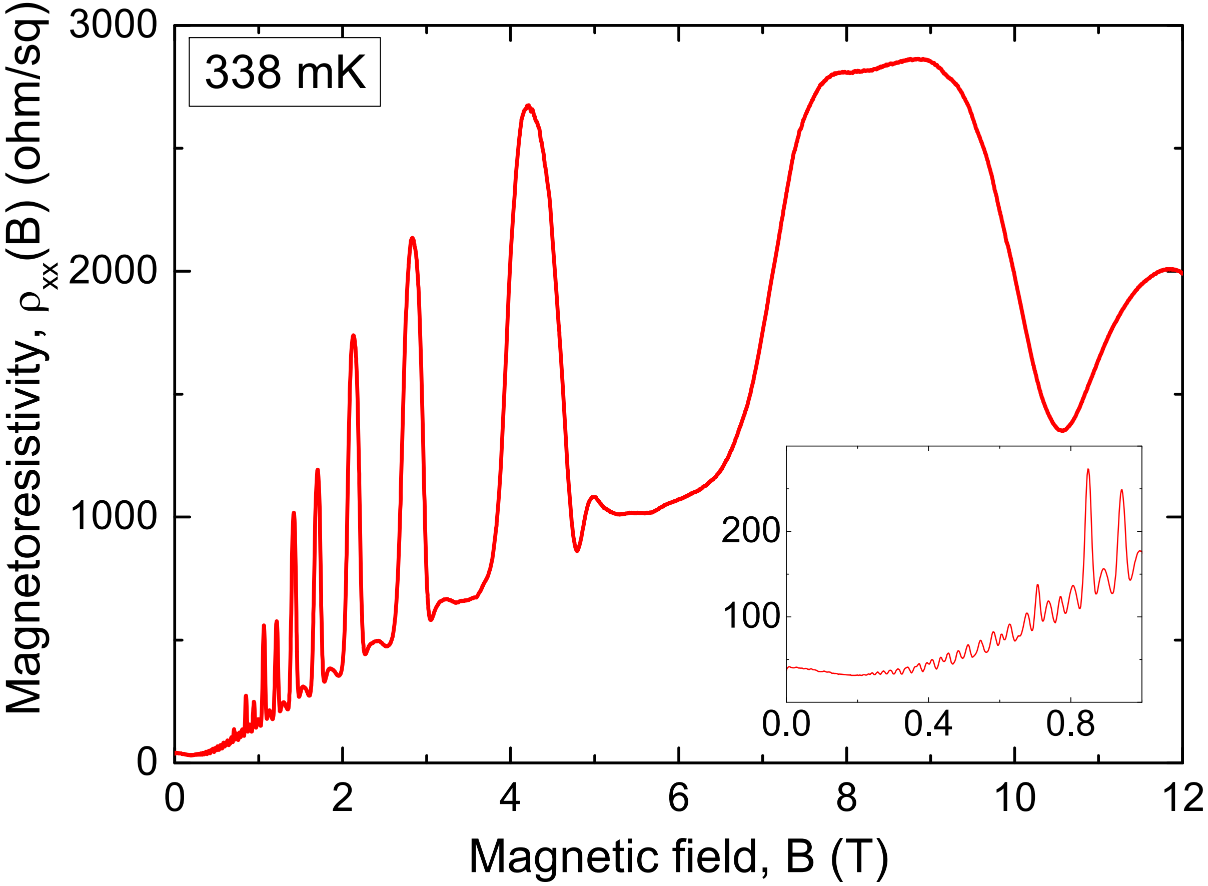


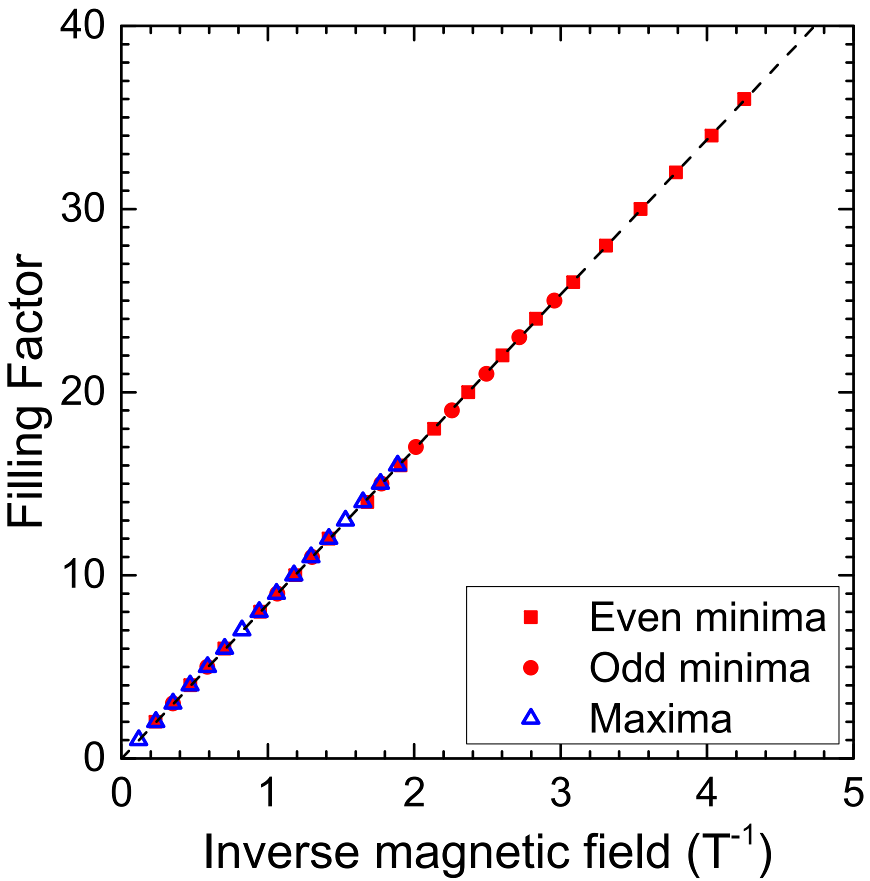
2 nm	Si cap
30 nm	$Si_{0.2}Ge_{0.8}$ cap
20 nm	B doped $Si_{0.2}Ge_{0.8}$ δB doped epilayer
20 nm	$Si_{0.2}Ge_{0.8}$ spacer
22 nm	⊕ ⊕ **2DHG** ⊕ ⊕ **strained Ge QW**
100 nm	$Si_{0.2}Ge_{0.8}$ buffer
1500 nm	RLG $Si_{0.24}Ge_{0.76}$ relaxed buffer
600 nm	Ge relaxed buffer
	Si(001) substrate

$p_{2DHG}(\text{model}) = 2.0\times10^{11}\ cm^{-2}$ $\quad$ $p_{2DHG}(\text{exp}) = 1.9\times10^{11}\ cm^{-2}$

Shubnikov-de Haas effect at 338 mK

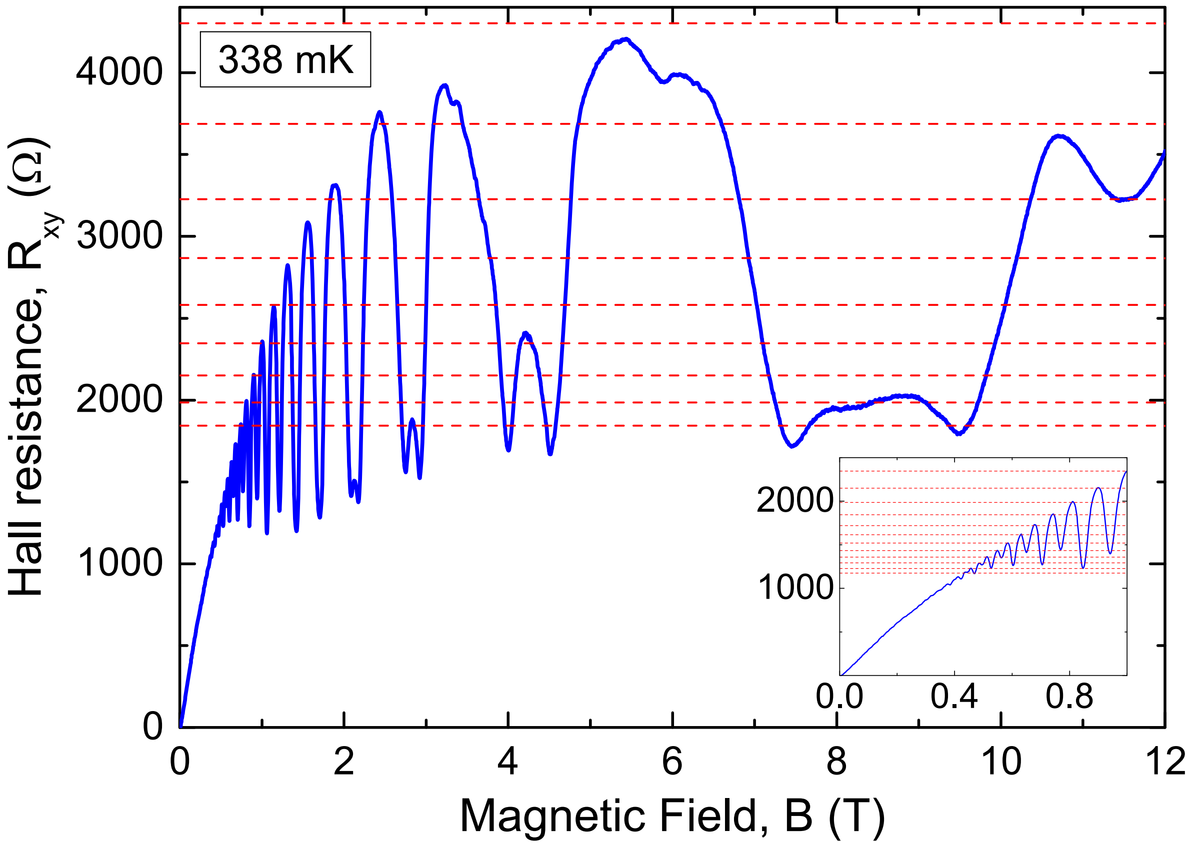
$p_{\mathrm{SdH}} = 2.0\times10^{11}\ \mathrm{cm}^{-2}$





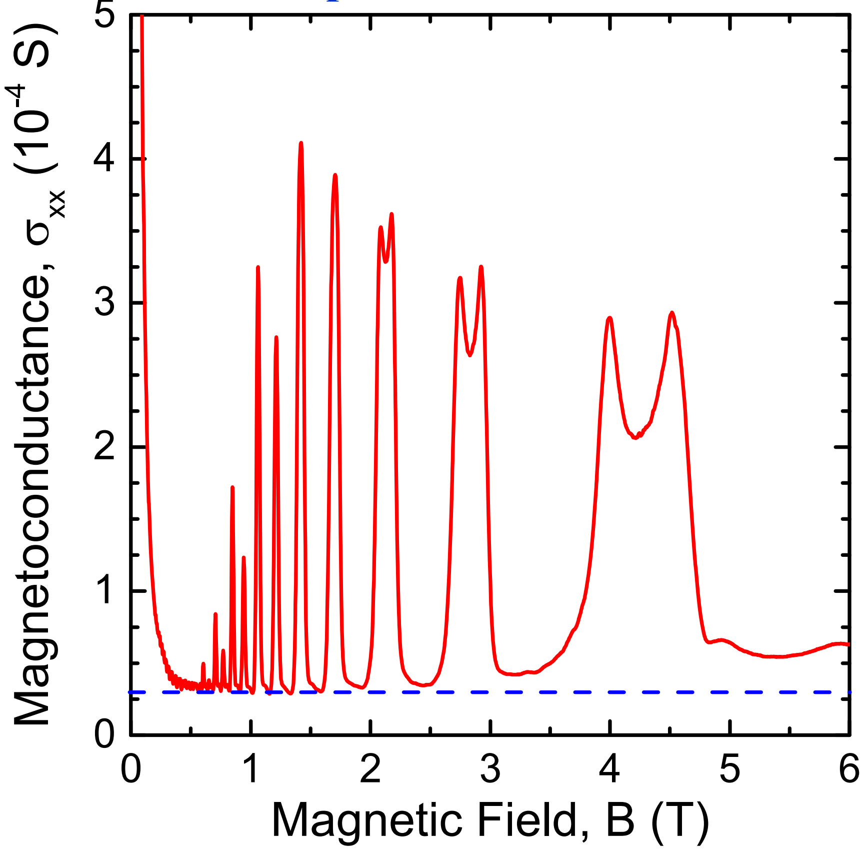
Quantum Hall Effect at 338 mK

$p_{\mathrm{Hall}} = 2.0\times10^{11}\ \mathrm{cm}^{-2}$



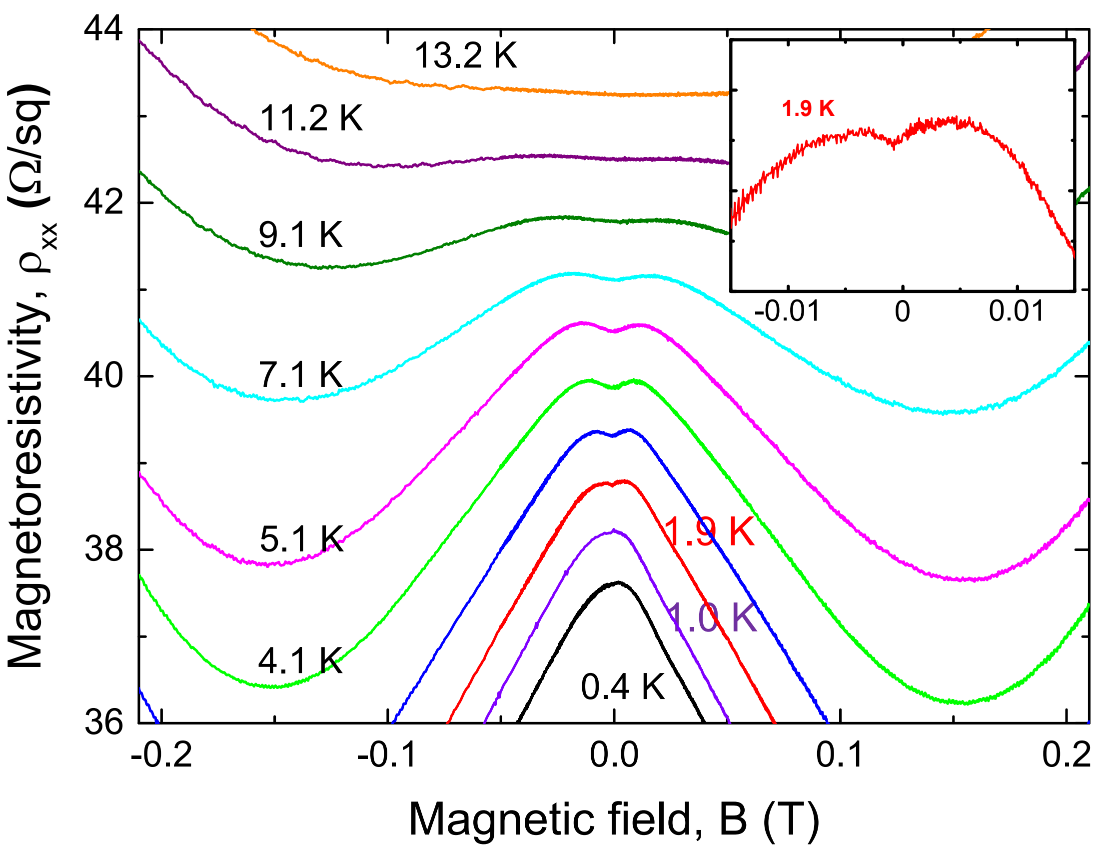
$\sigma_{\mathrm{2DHG}} = 24900\ \mu\mathrm{S}$

$\sigma_{\mathrm{parallel}} = 30\ \mu\mathrm{S}$



THE UNIVERSITY OF
WARWICK

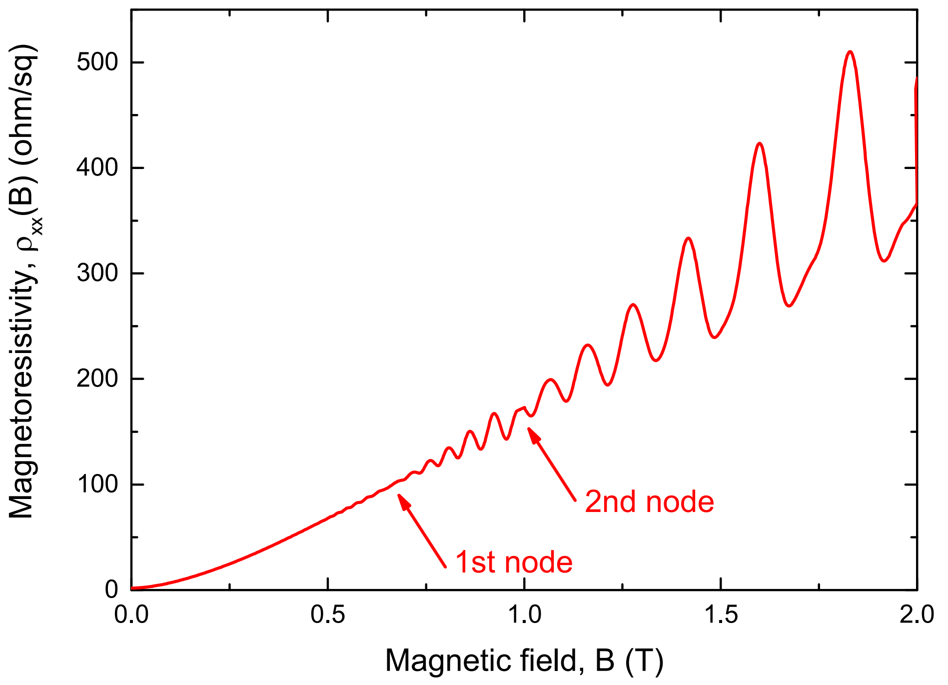
Observation of the weak antilocalization in Ge QW

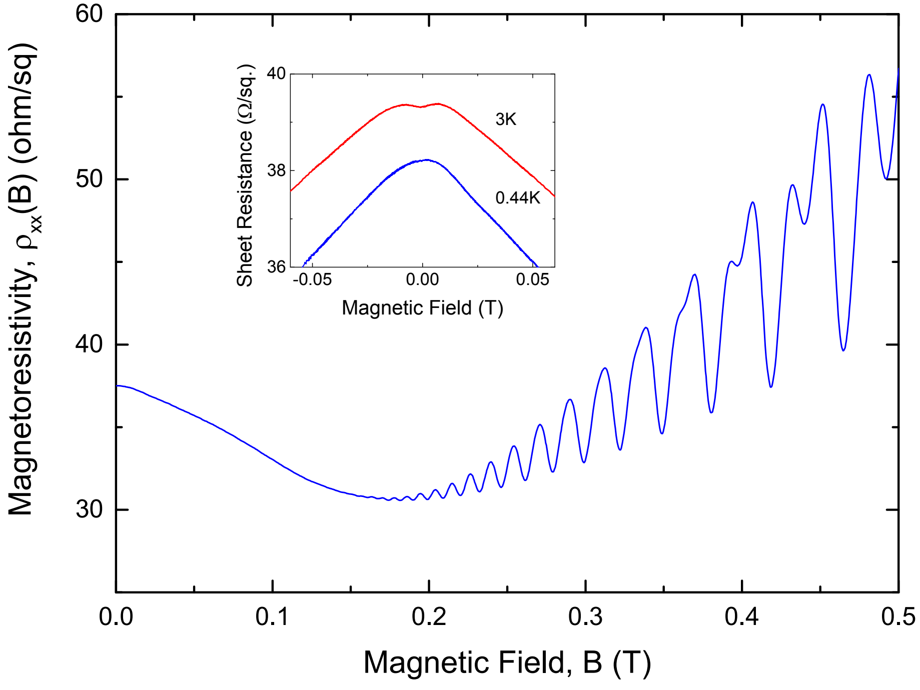


- Between 0.44 and 1K, the sample exhibits a negative MR associated with WL, which is completely supressed at a field strength of ~0.18 T.
- At 1.9 K, a very small region of positive MR is observed in the field interval of $-4\text{mT} < B < 4\text{mT}$, surrounded by a larger negative MR region
- Between 1.9 and 11.2K the peak gains an additional minimum at zero field resembling WAL behaviour.

J. Foronda, C. Morrison, J. E. Halpin, S. D. Rhead and M. Myronov "Weak antilocalization of high mobility holes in a strained Germanium quantum well heterostructure." Journal of Physics-Condensed Matter **27**(2) 022201 (2014).

Magnetoresistance at 400mk

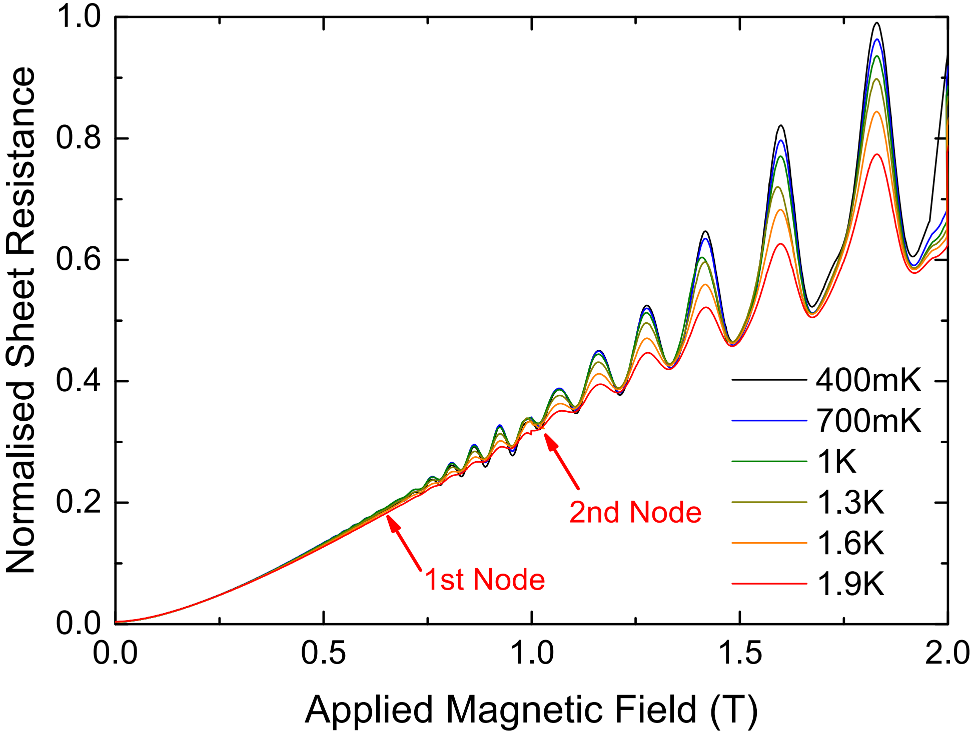

Inverted MOD


Normal MOD

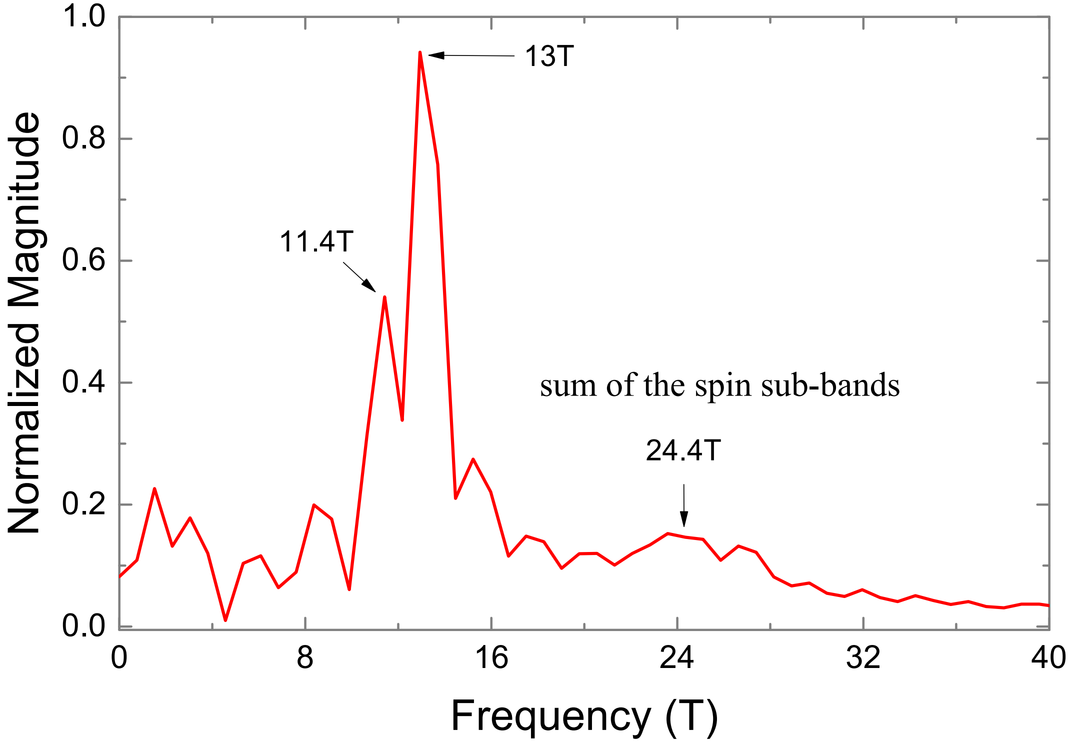
Sample	Hall mobility (cm^2/Vs)	Hall carrier density (cm^{-2})	Effective mass (m_0)	Dingle ratio α	Transport lifetime (ps)	Quantum lifetime (ps)
Inverted MOD	450,000	5.9×10^{11}	0.095	47.6	24	0.5
Normal MOD	777,000	1.9×10^{11}	0.065	18.1	29	1.6

THE UNIVERSITY OF WARWICK

Measurement of the interaction strength in Ge QW



spin split hole population



C. Morrison, P. Wisniewski, S. D. Rhead, J. Foronda, D. R. Leadley and M. Myronov "Observation of Rashba zero-field spin splitting in a strained germanium 2D hole gas." Applied Physics Letetrs **105**(18) 182401 (2014).

Calculation of Rashba parameter

Spin sub-band carrier densities (difference $\Delta p = p_{\uparrow} - p_{\downarrow}$) and total carrier density ($p = p_{\uparrow} + p_{\downarrow}$) can be calculated from Fourier transform peak positions. $p = \frac{fe}{\pi\hbar}$. Rashba parameter[1]:

For electrons: $\alpha_{SO} = \frac{\Delta p \hbar^2}{m^*}\sqrt{\frac{\pi}{2(p-\Delta p)}}$

For holes: $\boldsymbol{\beta_{SO} = \frac{\hbar^2}{2m^*}\sqrt{\frac{2}{\pi}}\frac{p(p_+-p_-)+\Delta p(p_++p_-)}{6p^2+2\Delta p^2} = 1.0 \times 10^{-28}\ eVm^3}$

Rashba spin-orbit energy:

For electrons: $E_{SO} = 2\alpha_{SO}k_F$

For holes: $\boldsymbol{E_{SO} = 2\beta_{SO}{k_F}^3 = 1.4\ meV}$

---

[1] *R. Winkler* "Spin Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems" (Springer-Verlag, 2003).

Key parameters comparison to other semiconductors

	AlGaN/GaN 2DEG[1] (L)	**GaSb/InAs 2DEG[2,3] (L)**	**InGaAs/InAlAs 2DEG[4] (L)**	**Ge 2DHG[7] (C)**	**Ge 2DHG[6] (C)**	**Si 2DEG[5] (L)**
Low temperature mobility (cm^2/Vs)	-	~20,000	95,000	450,000	~5,000	200,000
Rashba spin-orbit parameter α or β	**8.1×10^{-12} eVm**	**9×10^{-12} eVm**	**4×10^{-12} eVm**	**1×10^{-28} eVm^3**	**0.2×10^{-28} eVm^3**	**5.5×10^{-15} eVm**
Rashba spin-orbit energy E_{SO} (meV)	11.6	4.0	2.50	1.4	0.3	0.001
Lattice mismatch strain	…	…	…	0.8%	2.1%	…

[1] *Cho et al* Appl. Phys. Lett. **86,** 222102 (2005).
[2] *Luo et al* Phys. Rev. B **38**, 10142 (1988).
[3] *Luo et al* Phys. Rev. B **41**, 7685 (1990).
[4] *Das et al* Phys. Rev. B **39**, 1411 (1989).
[5] *Wilamowski et al* Phys. Rev. B **66**, 195315 (2002).
[6] *R. Moriya et al* Phys. Rev. Lett. 113, 086601 (2014).
[7] *C. Morrison et al* Applied Physics Letters **105**(18) (2014).

Conclusions

- High mobility strained Ge QW MOD heterostructures are an excellent playground to study quantum phenomena.

- The room-temperature 2DHG mobilities are the highest not only among the group-IV Si based semiconductors, but also among p-type III-V and II-VI ones.

- It has been shown that the Rashba SO interaction in strained Ge QW heterostructures can be identified and quantified using two complimentary low temperature magnetotransport techniques – Weak Anti-Localisation and Shubnikov de-Haas (SdH) oscillation frequency analysis.

- Ge QW heterostructures offer many promising opportunities for advancing our knowledge of spin interactions and producing spintronic devices.

- Very high quality strained Ge QW epilayers have been developed and appoint to a huge potential for further applications of such materials in ***variety of electronic, thermoelectric, photonic and spintronic devices*** on Si(001) or SOI(001) substrates.

Acknowledgements

Dr Christopher Morrison and Jamie Foronda

EPSRC

Engineering and Physical Sciences
Research Council